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Testing HMA Density with Electromagnetic Gauges

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Abstract
Electromagnetic gauges offer nondestructive testing of in-place HMA with real-time results for effective QC/QA decision making.

Keywords
Civil Construction and Environmental Engineering, CTRE

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Investigation of Electromagnetic Gauges for Determining In-Place HMA Density

Final Report
May 2007

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16. Abstract

Density is an important component of hot-mix asphalt (HMA) pavement quality and long-term performance. Insufficient density of an in-place HMA pavement is the most frequently cited construction-related performance problem.

This study evaluated the use of electromagnetic gauges to nondestructively determine densities. Field and laboratory measurements were taken with two electromagnetic gauges—a PaveTracker and a Pavement Quality Indicator (PQI). Test data were collected in the field during and after paving operations and also in a laboratory on field mixes compacted in the lab.

This study revealed that several mix- and project-specific factors affect electromagnetic gauge readings. Consequently, the implementation of these gauges will likely need to be done utilizing a test strip on a project- and mix-specific basis to appropriately identify an adjustment factor for the specific electromagnetic gauge being used for quality control and quality assurance (QC/QA) testing. The substantial reduction in testing time that results from employing electromagnetic gauges rather than coring makes it possible for more readings to be used in the QC/QA process with real-time information without increasing the testing costs.

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INVESTIGATION OF ELECTROMAGNETIC GAUGES FOR DETERMINING IN-PLACE HMA DENSITY

Final Report
May 2007

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EXECUTIVE SUMMARY

This study evaluated the use of electromagnetic gauges to nondestructively determine densities. Field and laboratory measurements were taken with two electromagnetic gauges—a PaveTracker and a Pavement Quality Indicator (PQI). Test data was collected in the field during and after paving operations and also in a laboratory on field mixes compacted in the lab.

Analyses of both devices indicate that both PaveTracker and PQI are sensitive to density changes due to roller passes. Sensitivity to density changes after roller passes is viewed as favorable since it indicates that these devices could be used for quality control. Statistical evaluations indicate that the majority of density readings obtained via electromagnetic gauges and cores differed. However, these differences do not relate whether the readings would affect overall quality assurance conclusions. To evaluate whether quality assurance conclusions would be altered by using an electromagnetic gauge, quality indices were calculated. The quality indices of the unadjusted data revealed that, even though the PQI readings tended to be much greater than the other two methods, quality assurance conclusions in most cases would be equivalent to ones obtained based on cores. The PaveTracker densities, if used for determination of payment, would have resulted in several contractors receiving a penalty.

This detailed study has found several mix- and project-specific factors that affect electromagnetic gauge readings. Thus, the implementation of these gauges will likely need to involve use of a test strip on a project- and mix-specific basis to appropriately identify an adjustment factor for the specific electromagnetic gauge being used for quality control and quality assurance (QC/QA) testing. The substantial reduction in testing time that results from employing electromagnetic gauges rather than coring makes it possible for more readings to be used in the QC/QA process with real-time information without increasing the testing costs. To ensure the appropriate implementation of electromagnetic gauges, there is a need for additional work that considers the following elements:

1. the utilization of test strips,

2. increased electromagnetic gauge testing frequency, and

3. new electromagnetic gauges that have entered the construction industry (e.g., PQI models 302 and 303). The PQI model 302 gauge has been available since 2005, and the 303 model's release is anticipated as soon as 2007.

1.0. INTRODUCTION

Density is an important component of hot-mix asphalt (HMA) pavement quality and long-term performance. Insufficient density of an in-place HMA pavement is the most frequently cited construction-related performance problem. Density is measured as part of the quality control process by the paving contractors and for the quality assurance process by the Iowa Department of Transportation (Iowa DOT). Contractors falling short of required density on placed HMA are paid less than the full contract amount, and payment factor discounts can range from 98 percent of the contract price to as low as 65 percent.

In Iowa, asphalt pavements are cored to determine in-place density and evaluate a contractor's compaction quality. The density of cores is measured in a laboratory in accordance with the American Association of State Highway and Transportation Officials (AASHTO) procedure AASHTO T 166, with a variation. The variation is that cores do not need to be dry in order to obtain their dry weight.

Unfortunately, the destructive process of coring creates holes in a new pavement and—even though they are repaired properly—creates imperfections in new pavements. Further, laboratory measurement of core samples is time-consuming as well as costly. Typically, core density results are not available until the next day at the earliest for making corrections to the paving process. Moreover, a number of other issues are associated with the coring process:

- Only seven cores are used to evaluate up to several miles of pavement.
- Validation of a contractor's density determination is only loosely determined.
- Current policies do not ensure that core possession is maintained by an owner/agency from sampling through testing.

Although nuclear density gauges allow for more rapid assessment of in-place HMA density during construction and have been used successfully to replace most coring in some states, they have many disadvantages. Owning and operating radioactive nuclear gauges requires strict licensing and usage procedures. The requirements include a state radioactive materials license, a radiation safety officer, dosimeter badges for operators, calibration and recalibration records, certification records of operators, and records on radiation badges. Other disadvantages include risk of exposure to radiation and the need to fulfill appropriate storage requirements.

Thus, there is a need for a rapid, non-intrusive, nondestructive, and non-radioactive method for HMA density measurement which is easy to use and reliable. Electromagnetic gauges that are now available have the potential to replace nuclear density gauges and address many of the issues associated with the coring process. The recently completed Federal Highway Administration (FHWA) Five-State Pooled Fund Study evaluated some of the non-nuclear density devices available and concluded that these devices provide results at least as good as nuclear density gauges. Now, research is needed to determine whether these gauges have the accuracy and precision required to be used for HMA density acceptance tests in Iowa.

Electromagnetic density gauges that are available have the potential to replace nuclear density gauges and the process of coring. These non-nuclear devices use electromagnetic fields to measure in-place density. The use of electromagnetic fields has the advantages of completely eliminating the licenses, training, specialized storage, and risks associated with devices that use a radioactive source and also being nondestructive (Romero 2002).

One of these electromagnetic density devices, called the Pavement Quality Indicator (PQI) was made commercially available by Trans-Tech Systems, Incorporated in 1998. Another of these devices, called the PaveTracker, was made commercially available by Troxler Electronics Lab. Both devices use a non-nuclear source, thus eliminating safety concerns associated with radioactivity. In general terms, both the PQI and PaveTracker operate on the principle of measuring changes in an electric field that result from the introduction of a nonconductor, known as a dielectric (e.g., HMA).

1.1. Objectives

The primary objective of this research is to establish the accuracy and precision of a PQI model 301 electromagnetic gauge manufactured by Trans-Tech and a PaveTracker model 2701 electromagnetic gauge manufactured by Troxler as compared to core testing. A subsequent objective is to determine which gauge, if either, should be considered for quality control and quality assurance in Iowa. Assuming a non-nuclear device or system is identified as a suitable replacement of core samples for evaluating in-place asphalt pavement density, an implementation plan will be developed to include recommended calibration procedures, methods for assessing measurement variability, and routine operation of the device or system for the Iowa DOT and participating contractors as well as their representatives.

1.2. Report Outline

A description of each method used to obtain densities along with related research can be found in section 2. In section 3, field sampling techniques for obtaining density readings are addressed. Analysis of PaveTracker field data is located in section 4, and PQI field data analysis is summarized in section 5. In section 6, a comparison between the two electromagnetic gauges and cores is summarized. Evaluations of laboratory density readings are related in section 7. Section 8 contains conclusions gleaned from observations and statistical analyses, along with recommendations.

2.0. LITERATURE REVIEW

The density of HMA is an important construction variable in the long-term durability of paved surfaces. Significant information exists regarding the important effect that in-place density (or air void content) has on the performance of HMA pavements. Whether the in-place density is specified as a percent of laboratory, control strip, or maximum theoretical density, it is well known and documented that density that is either too high or too low can lead to premature pavement failure (Killingsworth 2004). Lower percentages of in-place air voids can result in rutting and shoving, while higher percentages allow water and air to penetrate into a pavement, leading to an increased potential for water damage, oxidation, raveling, and cracking. Low in-place air voids are generally the result of a mix problem, while high in-place voids are generally caused by inadequate compaction (Brown et al. 2004).

Bulk specific gravity (G_{mb}) is defined as the ratio of the mass of a given volume of material at 25°C to the mass of an equal volume of water at the same temperature. The proper measurement of G_{mb} for compacted HMA samples is a major concern for the HMA industry, and this issue has become an even bigger problem with the increased use of coarse gradations. The volumetric calculations used during HMA mix design, field control, and construction acceptance are based upon bulk specific gravity measurements. During mix design, volumetric properties such as air voids, voids in mineral aggregates, voids filled with asphalt, and percent theoretical maximum density at a certain number of gyrations are used to evaluate the acceptability of mixes. All of these properties are based upon G_{mb}. Furthermore, an erroneous G_{mb} can lead to incorrect pay bonuses or penalties (Brown et al. 2004).

Current methods of measuring in-place density of HMA pavements have limitations. Laboratory density measurement of core samples (saturated surface dry, paraffin/parafilm coated, volumetric, and CoreLok) is time-consuming and costly. The alternative, a nuclear density gauge (which uses gamma ray technology), requires strict licensing and usage procedures and have other limitations (NCHRP 1999). For instance, a nuclear density gauge requires proper calibration and can take several minutes to obtain a density measurement, making it difficult to implement in real-time on a continuous paving operation (Jaselskis et al. 1998). Non-nuclear electromagnetic density gauges that have recently entered the market can potentially replace nuclear density gauges and the coring process. A brief description of each of these density measurement techniques follow.

2.1. HMA Density Measurement: Traditional Laboratory Methods

There are several methods used to determine densities of pavement specimens. The following sections outline the most popular methods currently used.

2.1.1. Saturated Surface Dry (SSD) Method

The water displacement method, or saturated surface dry (SSD) method (AASHTO T166 or ASTM D2726), is the most common method used to determine bulk specific gravity of compacted hot-mix asphalt. This method consists of first weighing a dry sample in air, then obtaining a submerged mass after the sample has been placed in a water bath for a specified time interval. Upon removal from the water bath, the SSD mass is determined after patting the sample dry using a damp towel (see Figure 1). Based upon Archimedes' principle, the SSD method approximates the volume of a compacted asphalt specimen as the volume of water displaced when submerged under water (Tarefder, Musharraf, and Kenneth 2002).

Figure 1. Blotting an HMA specimen dry (Indiana DOT 2006)

According to the AASHTO T166 and ASTM D2726 procedures, tests are only valid for specimens (cores) with water absorptions of less than two percent and no open or interconnecting voids. Also, the reliability of the water displacement method decreases with increasing depth of the surface irregularities and the presence of interconnected voids that are open to the surface of the solid (InstroTek 2001).

In order to determine the bulk specific gravity using the water displacement method, three weights of a specimen must be obtained. First, the dry weight of a specimen must be obtained. Second, the weight of the specimen after being under water for four minutes must be recorded. Finally, the weight of a specimen having a saturated surface dry condition is determined. This SSD condition is very difficult to determine, as it is subject to individual interpretation of when a specimen is SSD and, thus, the procedure is prone to variability and error. The following expression is used to compute the bulk specific gravity using the SSD method:

$$Bulk\ Specific\ Gravity\ at\ 25^{o}\,C = \frac{A}{B-C} \tag{1}$$

where *A* is the mass of the dry specimen in air, *B* is the mass of the saturated surface dry specimen in air, and *C* is the mass of the specimen in water.

The SSD method has proven to be adequate for conventionally designed mixes, such as those designed according to the Marshall and Hveem Methods, that generally utilize fine- and dense-graded aggregates. Historically, mixes were designed to have gradations passing close to or above the Superpave-defined maximum density line (e.g., fine-graded). However, since the adoption of the Superpave mix design system and the increased use of stone matrix asphalt (SMA), mixes are being designed with coarser gradations than in the past (Brown et al. 2004).

The potential problem with measuring the G_{mb} of mixes like coarse-graded Superpave and SMA using the SSD method comes from the internal air-void structure of these mix types. These types of mixes tend to have larger internal air voids than finer, conventional mixes that have similar overall air-void contents. Mixes with coarser gradations have a much higher percentage of large aggregate particles. At a certain overall air-void volume—which is mix-specific—the large internal air voids of the coarse mixes can become interconnected. During G_{mb} testing with the SSD method, water can quickly infiltrate the sample through these interconnected voids. However, after removing the sample from the water bath to obtain the saturated-surface dry condition, the water can also drain from the sample quickly. This draining of the water from the sample causes errors when using the SSD method (Brown et al. 2004), as the displaced volume is lower than it would otherwise be.

2.1.2. Paraffin and Parafilm Method

The paraffin and parafilm methods—as described by AASHTO T275 (Bulk Specific Gravity of Compacted Bituminous Mixtures using Paraffin Coated Specimens) and ASTM D1188, respectively—address the water absorption problems inherent in the water displacement method. AASHTO T275 should be used with samples that contain open or interconnecting voids, absorb more than two percent of water by volume, or both. In this method, the mass of the HMA sample is determined before coating it with liquid paraffin wax. The sample is then weighed in air and under water.

Figure 2. Parafilm application (Muench, Mahoney, and Pierce 2005)

The compacted HMA specimens are either coated with paraffin or wrapped in parafilm (see Figure 2). The use of paraffin or parafilm can be time consuming, awkward to perform, and messy (Buchanan 2000). The paraffin coating also may limit further evaluation of a specimen after the G_{mb} testing is completed, whereas the parafilm is easily removed to allow for further testing. The testing procedure is similar to that of AASHTO T166 and ASTM D2726. First, the dry, uncoated weight of a sample is determined. Second, the mass of a completely coated specimen is obtained. Next, the mass of the coated sample under water is determined. Finally, the specific gravity of the coating (paraffin or parafilm) is determined as outlined in ASTM D1188. The G_{mb} of the film-coated specimen is computed using the following formula:

$$Bulk\ Specific\ Gravity = \frac{A}{\left\{D - E - \left(\dfrac{D - A}{F}\right)\right\}} \tag{2}$$

where A is the mass of the dry specimen in air; D is the mass of the dry, coated specimen; E is the mass of coated specimen under water; and F is the specific gravity of the coating as determined at 25°C.

Unfortunately, the AASHTO T275 test method used for sealing compacted asphalt samples can have poor repeatability and high sensitivity to operator involvement and training. Furthermore, there are currently no specifications for sealing samples 150 mm in diameter. Consequently, few agencies use this method (Bhattacharjee, Mallick, and Mogawer 2002).

For open- and coarse-graded mixes, the density results obtained by both the SSD and parafilm methods are higher than the actual density of a specimen. Problems related to inaccurate specific gravity measurements can have serious and detrimental effects on design and quality control of asphalt mixtures. Inaccurate air-void contents values, based on erroneous specific gravity values, can seriously affect the performance and quality of roadways.

2.1.3. CoreLok

In the past several years, vacuum-sealing technology using a CoreLok device has been employed by a number of researchers and transportation agencies to determine an HMA G_{mb} (see Figure 3). ASTM D 6752 (Standard Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Automatic Vacuum Sealing Method) has recently been approved, outlining the G_{mb} determination procedure with the CoreLok device (Buchanan and White 2005).

Figure 3. CoreLok Vacuum Sealing Device (Buchanan and White 2005)

A CoreLok device has been developed to determine the G_{mb} of coarser-graded Superpave mixtures. A CoreLok device is a vacuum sealing method that eliminates the need for the SSD-condition weighing. Through the use of flexible, puncture-resistant vacuum bags, a sample is sealed and remains dry during testing (InstroTek 2003). The process of determining the bulk specific gravity with the CoreLok system is similar in nature to AASHTO T275 and ASTM D1188 (which use paraffin wax and parafilm, respectively) to prevent water infiltration from occurring during the sample's submersion. The CoreLok device can accommodate 4-inch-diameter, 6-inch-diameter, and even beam specimens.

The CoreLok system requires very little involvement from the operator, which means that the test results may be more reproducible. Also, when compared to dimensional analysis and the water displacement method, the CoreLok method has the smallest multi-operator variability, as defined by a standard deviation of test results (Hall, Griffith, and Williams 2001).

Research conducted by Buchanan (2000) concludes that the CoreLok procedure can determine G_{mb} more accurately than such conventional methods as SSD, parafilm, and dimensional analysis (e.g., mass divided by volume). Theoretically, there should be no instance where a CoreLok G_{mb} is greater than a SSD G_{mb}. As a specimen's air voids and surface texture decrease, the results of CoreLok and water-displacement procedures should approach the same value (Buchanan and White 2005).

Crouch et al. (2002) reported that the CoreLok device had good performance with a variety of sample types and was the most widely applicable method of G_{mb} determination. Results from a round-robin study (Cooley, Prowell, Hainin, et al. 2002) conducted by the National Center for Asphalt Technology (NCAT) showed the CoreLok procedure to be a viable method for determining the G_{mb} of HMA mixes. The report further stated that the CoreLok procedure provided a more accurate measure of G_{mb}, especially for mixes with high water-absorption levels, as compared to water-displacement procedures.

The CoreLok method utilizes an automatic vacuum chamber with specially designed resilient and puncture-resistant bags. Using a 1.25-hp vacuum pump, the unit automatically evacuates and seals the bag during the vacuum operation. The vacuum pump is capable of pulling up to 30 in. Hg (1 Torr). The bags are designed in two different sizes to accommodate different asphalt sample sizes. The following steps are used in determining G_{mb} with the CoreLok procedure (InstroTek 2003):

1. Use the plastic specimen bag's predetermined density, or determine the density by using the standard aluminum reference cylinder provided.
2. Place the compacted HMA specimen (either a core or laboratory-compacted specimen) into the bag.
3. Place the bag and specimen inside the CoreLok vacuum chamber.
4. Close the vacuum chamber door, at which time the vacuum pump will start and evacuate the chamber to 30 in. (760 mm) Hg.
5. In approximately two minutes, the chamber door will automatically open with the specimen completely sealed within the bag and ready for water-displacement testing. The user should ensure that the bag seal is secure before proceeding to Step 6.
6. Perform water-displacement method testing of the sealed specimen according to AASHTO or ASTM standards. Correct the results for the bag density and the displaced bag volume, as suggested by ASTM D 1188. Use the following equation to calculate the bulk specific gravity of the sample:

$$Bulk\ Specific\ Gravity = \frac{A}{\left\{B - E - \left(\frac{B - A}{F_T}\right)\right\}} \tag{3}$$

where *A* is the mass of the dry specimen in air, measured in grams; *B* is the mass of dry, sealed specimen, in grams; *E* is the mass of the sealed specimen underwater, in grams; and F_T is the apparent specific gravity of the plastic sealing material at 25°C (77°F), as provided by the manufacturer.

Buchanan and White (2005) investigated the G_{mb} differences between water-displacement and CoreLok vacuum-sealing procedures and the resulting changes in volumetric properties and design asphalt contents for various Superpave mix designs. The results of their study showed significant G_{mb} differences between CoreLok and water-displacement procedures, with the CoreLok procedure yielding slightly lower G_{mb} values. The observed differential between CoreLok and water-displacement G_{mb} values increased as water absorption increased for coarse-graded mixes but was generally constant for fine-graded mixes. HMA gradation most significantly affected G_{mb} differences between CoreLok and water-displacement procedures. Based on their research findings, Buchanan and White (2005) recommended that the CoreLok device be considered for use in order to more accurately determine specimen G_{mb}—especially for coarse-graded mixes—during HMA mix design and quality control/quality assurance testing.

As part of an ongoing study on HMA permeability testing, Bhattacharjee, Mallick, and Mogawer (2002) evaluated the G_{mb} values of several dense-graded mixes with coarse and fine gradations from three New England states. Based on their results from both the SSD and the CoreLok vacuum seal method., the latter method provides a better estimation of air voids in a compacted HMA mix for coarse- and fine-graded mixes with high air voids.

Although the CoreLok method has significant potential for use in the asphalt industry, the repeatability and reproducibility of the procedure needs to be evaluated before the device can be specified by agencies (Cooley, Prowell, Brown, et al. 2002).

2.2. HMA Density Measurement: Nuclear Density Gauges

The most common nondestructive method for measuring in-place density of HMA involves the use of a nuclear density gauge. The general observation is that measuring density with a nuclear gauge in the field is not as accurate as measuring the density of cores in the laboratory. Many variables are known to impact nuclear gauge readings, and it has been speculated that changes in technique could improve accuracy (Padlo et al. 2005).

Surface nuclear density gauges use the interaction of gamma radiation with matter to measure density through direct transmission or backscatter. The gamma ray method is simple and nondestructive. As shown in Figure 4, the gamma ray method for bulk specific gravity measurement is based on the scattering and adsorption properties of gamma rays with matter (Malpass and Khosla 2002).

The gamma rays at a specific energy interact with matter through the mechanism known as Compton scattering, or inelastic scattering. As gamma rays pass through a sample, collisions occur between the photons of the gamma rays and electrons in the specimen. These collisions cause the photons to lose energy and change directions as they pass through the sample. Compton scattering is a function of electronic specific gravity of the material—hence, a function of the mass specific gravity of the material—and with proper calibration, the photon count is directly converted to the bulk specific gravity of the specimen (Malpass and Khosla 2002). Most nuclear gauges use Cesium-137 as the nuclear source for density measurements. Once the source is released, the readings are dependent upon the duration, since the count is based upon the return of nuclear particles to the source.

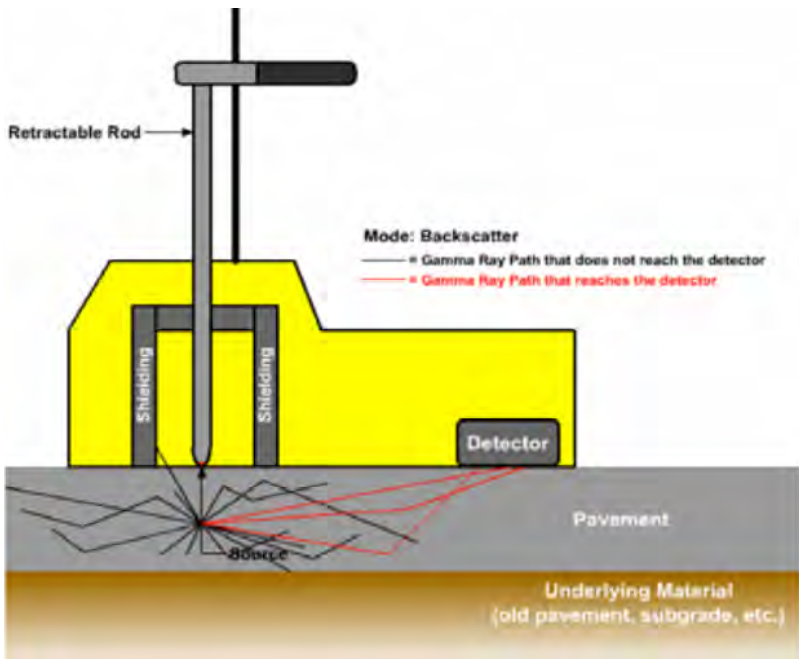

Figure 4. Nuclear density gauge gamma ray technology (Muench, Mahoney, and Pierce 2005)

Advantages of the gamma ray method include its quickness and the fact that it requires limited human intervention. However, because the method is relatively new, more research needs to be conducted to ascertain its role for determining bulk specific gravity of compacted HMA specimens. In addition, both accuracy and length of time for testing are important issues (Williams, Duncan, and White 1996). Furthermore, the depth of the layer to be tested is also important; 95 percent of the reading is obtained in the top two inches of the HMA layer, with an infinite depth assumed at five inches.

The nuclear density gauge must be calibrated, preferably against actual core densities obtained from the same material it will be used to measure (Mitchell 1984). Usually, nuclear gauges are calibrated at the factory by establishing a relationship between the counts and known density blocks (Zha 2000). The gauge calibration will change with time due to rugged use, the rough construction industry environment, changes in the gauge's mechanical geometry, degradation of the radioactive source, and/or the electronic drift of the gauge's components (Zha 2000). Even with perfect calibration, the nuclear gauge can show misleading HMA density values resulting from (1) the influence of the environment surrounding the equipment or (2) variations in the material, surface texture, aggregate types, temperature, and moisture (Burati and Elzoghbi 1987; Sanders, Rath, and Parker 1994; Mitchell 1984). Proper field adjustments can compensate for most of these factors, but questions regarding the overall accuracy and consistency of the nuclear gauge remain (Padlo et al. 2005).

The HMA mat thickness is one factor that is considered to affect the nuclear gauge accuracy. In order to obtain nuclear density results, some gauges require that a thickness value be keyed into the instrument. The keyed-in value is the specified project thickness and does not necessarily reflect the exact thickness of the test location. Such conditions may influence the nuclear gauge readings (Parker and Hossain 1995; Stroup-Gardiner and Newcomb 2000).

Even if the actual thickness were known with certainty, it would be possible for each nuclear gauge model to measure a different pavement depth, which could cause variability in the resultant density measurement (Padlo et al. 2005). For example, the radioactivity could travel through two layers when the top layer is two inches thick and the bottom layer is four inches thick, producing a density based upon two layers. It has been suggested that some pre-construction surface treatments such as milling (if performed properly and without rip-outs) may reduce the variability in nuclear density readings caused by inconsistencies in the existing pavement layer.

Finally, the surface texture of the rolled material may affect nuclear gauge density readings. The surface on which the nuclear gauge rests may have aggregates raised above the mean pavement surface, thus leading to higher air-void content value to be used in the density calculation. A California study found that there is no need to utilize known-density material, such as rubber pads, to eliminate protrusions or irregularities on the surface of HMA. Currently, nuclear gauge operators must pay close attention to the surface on which the nuclear gauge rests, to ensure maximum surface contact between the nuclear density gauge and the pavement surface (Padlo et al. 2005).

Because it provides nondestructive density measurements within one to five minutes, the nuclear gauge saves time and money compared to core extraction. However, the nuclear gauge is generally more variable than core measurements, and the quality of the data obtained from a nuclear gauge is dependent on a good correlation with core data from the project. Furthermore, special training and certification is required of anyone that operates a nuclear density gauge, and any inconsistencies in the manner of handling the gauge between readings can result in operator error, further affecting the variability of the measurements (Hausman and Buttlar 2002).

Previous studies performed in California, Pennsylvania, Virginia, Nevada, Texas, Maine, and Connecticut have yielded similar conclusions regarding the use of nuclear density gauge readings. Each study determined that the nuclear gauge should not be used for quality assurance and should remain only as a quality control tool in the field (Choubane et al. 1999; Parker and Hossain 1995; Stroup-Gardiner and Newcomb 2000; Padlo et al. 2005).

2.3. HMA Density Measurement: Non-Nuclear Density Gauges

Recently, non-nuclear electromagnetic density gauges have entered the market, which have the potential to replace nuclear density gauges and the coring process. These non-nuclear devices use electromagnetic signals to measure in-place density. The use of electromagnetic signals has the advantages of completely eliminating the licenses, training, specialized storage, and risks associated with devices that use a radioactive source, while also being nondestructive (Romero 2002).

The first of these non-nuclear density devices, the Pavement Quality Indicator (PQI), was made commercially available by Trans-Tech Systems Inc. in 1998 (see Figure 5). The second of these devices, the PaveTracker, was made commercially available by Troxler Electronics Lab (see Figure 6). Both devices feature a non-nuclear source, thus eliminating safety concerns.

Figure 5. Pavement Quality Indicator (TransTech 2002)

Figure 6. PaveTracker (Troxler 2003)

In general terms, both the PQI and PaveTracker operate on the principle of measuring changes in the electric field that result from the introduction of a dielectric (e.g., HMA). The PQI measures bulk density or the degree of compaction through an electrical sensing field that responds to changes in electrical impedance of the material matrix which, in turn, is a function of the composite resistivity and dielectric constant of the material (NCHRP 1999).

Whenever an electrical charge is applied to a conductor, an electrical field is produced. If a nonconductor, known as a dielectric, is introduced inside this electric field, the strength of the field is reduced. The amount by which this dielectric reduces the electrical field can be characterized by the dielectric constant. In order to use the dielectric constant as a measure of asphalt concrete density, the strength of an electrical field is measured. This measurement must first be taken on an asphalt concrete sample of known density. The constituents of asphalt concrete—asphalt binder, aggregates, air, and moisture—each have different dielectric constants. As the asphalt concrete is compacted (i.e., as the density increases), the ratio of the volume of air to that of the other components changes, causing a change in the dielectric constant of the system. The change in dielectric constant causes a change in the electrical signal. Since the amount and type of material remains constant (except for air), this change in the electrical signal is related to the change in density (Wen and Bahia 2004). The operational theory schematic of the PQI is shown in Figure 7.

The first generation PQI machines were capacitance-based measuring systems (Patent No. US 5,900,736), while the new 301 model (Patent No. US 6,414,497) is impedance-based. The PQI provides a sensor with a multi-configuration geometry that provides an electrical field with a controllable depth of penetration. This attribute is an innovation not previously available from devices in current use (Glagola 2003).

As shown in Figure 7, the PQI system provides an electronic circuit that generates a radio frequency voltage that is applied to one sensing electrode, generating an electrical field in the paving material. A second sensing electrode measures the dielectric response of the paving material. A data processor determines the density of the paving material based on the measured complex impedance of the paving material. The data processor computes the accurate relative density, corrected for moisture that is present in or on the paving material. Corrections for influences outside of the desired measure (material density) are incorporated into the system. These automatic corrections account for surface moisture, temperature variation, and sensor impedance. This automatic corrective action provides realistic density readings under varying conditions without requiring cumbersome manual adjustments to data (Glagola 2003).

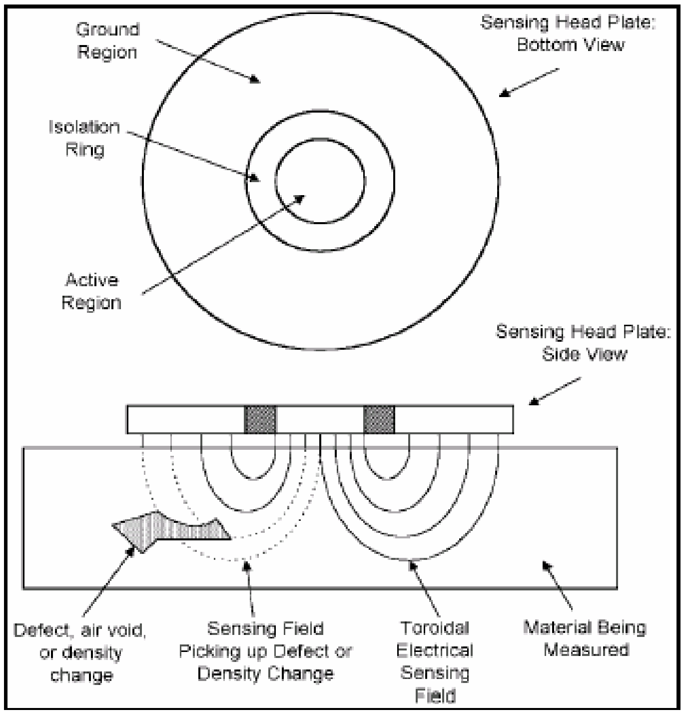

Figure 7. Operational theory schematic of PQI and PaveTracker (NCHRP 1999)

The PQI system has been designed to be adaptable to onsite conditions. Another innovation is the ability to change the sensor configuration, under computer control, to specify the depth to be tested. This is particularly important when testing at a joint in the pavement between two different applications of asphalt. Adjustability of the sensor configuration is also advantageous to the system because the sensor configuration dictates the depth of penetration and area of electrical field and, accordingly, the volume of the field of test. For instance, operation of a smaller sensor allows the depth of penetration to be reduced. The ability to accurately control the depth of penetration prevents imprecise determinations that can result when the signal penetrates through a new paving lift coat into an underlying surface that may not have the same density. The PQI system provides a constant-voltage source circuit, enabling the system to detect material density with more accuracy and reliability than other devices. A precision-constant voltage source provides a stable system that cannot be altered by environmental factors, such as electromagnetic interference (Glagola 2003).

The examination of the underlying principles of the PQI and the PaveTracker (i.e., that of dielectric constant and permittivity) are critical in assessing the capabilities and potential limitations of the technologies. Permittivity, ε, describes the interaction of a material with an electric field. The dielectric constant, ε', is equivalent to relative permittivity ($\varepsilon_r = \varepsilon/\varepsilon_0$). Permittivity consists of real and imaginary components. The relationship can be described as follows:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} = \left(\frac{\varepsilon_r'}{\varepsilon_o}\right) - j\left(\frac{\varepsilon_r''}{\varepsilon_o}\right) \tag{4}$$

where ε_r is the complex relative permittivity, ε_o is the permittivity of free space, ε'_r is the real part of permittivity, ε''_r is the imaginary part of permittivity, and j is the current density (Williams 1996).

The real part of permittivity is a measure of how much energy from an external electric field is stored in a material; it is usually greater than one for solids and liquids. The imaginary part of permittivity is also called the loss factor, and it is a measure of dissipativeness of a material when exposed to an external electric field. The loss factor is always greater than zero, but is usually much smaller than the real portion. The loss factor includes the effects of both dielectric loss and conductivity (Williams 1996).

Many studies have compared the accuracy of nuclear density gauge measurements with those of non-nuclear measuring devices like the PQI. The accuracy and reproducibility of the PQI and a nuclear measuring device for determining the in-place density of compacted asphalt concrete pavements was evaluated by Sully-Miller Contracting Company (2000). Based on their limited study (with a corrected gauge-to-core bias), it was reported that TransTech's PQI model 300 is a reliable and accurate instrument to measure in-place density of compacted asphalt concrete. It was further reported that the PQI is very user friendly and, being lighter, causes less physical strain on the back of the technicians. It can be stored and transported anywhere and can be purchased without a radioactive materials license. It is fast and has good repeatability as well as a low standard deviation between tests. Unlike the nuclear gauges, it does not require extensive and periodic calibrations either by the manufacturer or state agency.

In Pennsylvania, the state's Innovations Council also evaluated the PQI system against a nuclear gauge. Results from this study include data regarding the costs of training and operating, which are provided in Figure 8 (Glagola 2003).

<u>NUCLEAR GAUGE (initial cost)</u>		
Trainer (1-day)	$180	= $180
Salary of Personnel for 1 day training	$140 x 5 people	= $700
Two Week OJT W/licensed operator	$140 x 5 people x 5 trainers x 10 days	= $35000
Radiation Badges	$3.65 x 4/year x 5 people	= $73
Annual Gauge Re-calibration	$386 x 5 gauges	=$1930
Storage/Transportation		Non-reportable
Total		= $37883
<u>TRANSTECH PQI SYSTEM (initial training)</u>		
Trainer (2 hours)	$45	= $45
Salary of Personnel for 2 hours training	$36 x 5 people	= $175
Total Training Cost PQI		= $220
TOTAL SAVINGS (initial training)	**$37883 - $220**	**= $37663**
USAGE COSTS (over 5 year period)		
Final figures for operational cost savings use over a 5-year period:		**= $12655**
TOTAL 5-YEAR SAVINGS (using the PQI system)		**= $50318**

Figure 8. Cost comparison between the PQI and a nuclear gauge (Glagola 2003)

It should be noted that the measurement mechanisms of the nuclear devices and non-nuclear electromagnetic devices are different. While the nuclear density gauges measure the actual density (absolute value) of the material, the non-nuclear electromagnetic devices indicate the density (relative value) of the material by detecting the dielectric component of the material density and relating that to a density value. As the asphalt is compacted, the air voids in the mix decrease and the dielectric properties change; therefore the non-nuclear devices report this change as an increase in the density. Cores with known density for each mix have to be available to use a PQI and PaveTracker successfully.

Both the PQI and PaveTracker offer several potential advantages, including (1) there is no threat of exposing workers to radiation, (2) they are lightweight, (3) nuclear licensing and training are not required, reducing operating costs, and (4) readings are faster than with a nuclear density gauge—almost instantaneous (Karlsson 2002; Asphalt Contractor 1998).

2.4. Evaluation of PQI and PaveTracker

A number of research studies have been conducted to evaluate the PQI and the PaveTracker, especially use of the PQI for measuring in-place HMA density. The most notable study was the multi-state pooled-fund study by Romero (2000; 2001). This study was led by Maryland State Highway Administration with participation from the Federal Highway Administration and the state highway agencies of Pennsylvania, New York, Connecticut, Oregon, and Minnesota. The study consisted of two phases: lab tests and field tests. The results of lab testing were very promising; the PQI 300 model density measurements highly correlated with the densities of HMA slabs (Romero 2000). However, the results of field tests indicated that the PQI 300 did not perform as well as the nuclear gauges (Romero 2001).

After PQI equipment calibration by TransTech Systems, the test results by PQI were improved significantly in the 2002 field tests. Note that the PaveTracker device was added to the field tests only in 2002. The final report concluded that use of the PQI for providing quality control during paving is a perfectly acceptable method and that this device provides results at least as good as the available nuclear devices (Romero 2002). The final reports of both lab and field tests are available for this study (Romero 2000; Romero 2001; Romero 2002; Romero and Kuhnow 2002).

A comparison of other research studies on the performance of non-nuclear gauges yields mixed results or findings. Henault (2001) evaluated the PQI model 300 on ten projects in Connecticut, comparing the non-nuclear results with cores. The PQI model 300 was not recommended for quality control or quality assurance testing in Connecticut since the PQI model 300 densities did not compare well with core densities. Henault (2001) believed that poor correlations of the non-nuclear gauges may have been due to the effects of moisture. Wisconsin Department of Transportation (WSDOT) performed studies on PQI 300 with comparison to cores in 2001 and concluded that PQI 300 tracked the core densities well (Wen and Bahia 2004).

The results from the field projects conducted as part of NCHRP Project 9-15 (2004) showed that the variation among the PQI, a nuclear density gauge, and core measurements were statistically the same. These results are only applicable to dense-graded HMA mixtures. Some studies have reached different conclusions but, within the confines of this project, it has been demonstrated that the expected variability among the three different measurement methods is similar, even if the measured means are not equal in all cases.

Hausman and Buttlar (2002) conducted both laboratory and field studies to evaluate factors affecting the PQI model 300 in Illinois. It was reported that moisture and temperature effects still needed to be considered with the model 300. During field testing on three projects, the PQI did not perform as well as nuclear gauges; it had a higher standard error versus the line of equality. Based on the results from this study, the PQI model 300 was not recommended for quality control or quality assurance testing in the state of Illinois.

Allen, Schultz, and Willet (2003) evaluated PQI 300 in Kentucky on a single construction project. Based on the research findings, it was recommended that, since the PQI most closely approximated the data from the cores (by comparing both the means and the distributions derived from several devices), a PQI could be used for quality control on HMA paving mats without sacrificing density or quality.

Recently, Wu (2005) evaluated the variability of air voids of plant-produced HMA mixtures and compared the different methods of air void measurements by studying four rehabilitation projects in Louisiana. The PQI model 301 was evaluated, and the results were compared with conventional AASHTO T 166 core densities and CoreLok results. The results showed a strong correlation between air voids measured using conventional and CoreLok methods. Correlations between PQI-measured air voids and the other two methods were reported to be fair. Note that a PQI can be set to read either percent compaction or percent air voids (TransTech 2002).

Recently, PQI manufacturer TransTech conducted an assessment of field asphalt density gauge data, comparing the results to those of cores processed according to AASHTO T-166 (TransTech 2004). Factors that can affect bias, repeatability, reproducibility, and stability were carefully controlled to determine the influence of each on the overall measurement process. Each of these parameters was evaluated in a deterministic sequence that was designed to isolate the effects of each. Defined processing of the parameters determined the effect of each on the overall measurement and whether any of the factors prevented a gauge from meeting overall accuracy requirements when measuring a specified material, such as asphalt pavement. The data acquisition procedure involved calibrating the instruments to the mat/mix by adjusting the offsets of the gauges so that the mean of a set of reference gauge readings and core readings were the same. The second activity involved taking the actual core and gauge data. The PQI and nuclear gauge readings were taken prior to removing each core. A linear correlation analysis was performed on the dataset to determine if a statistically significant linear relationship exists between the gauge data and the core data. The results of regression analysis conducted by TransTech are plotted in Figure 9.

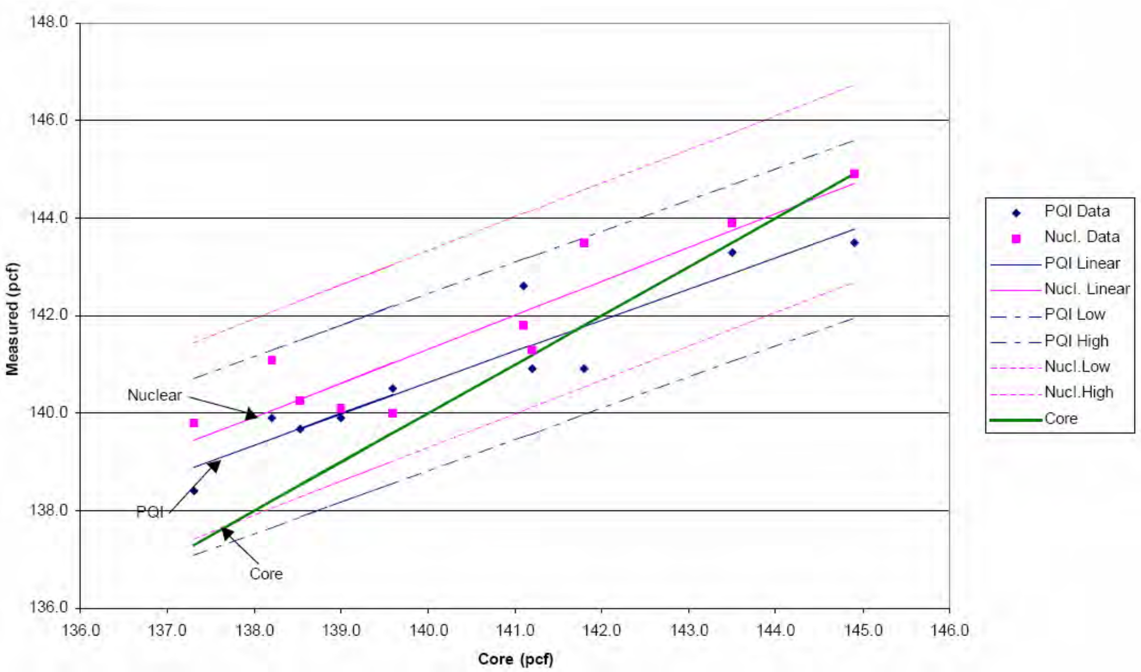

Figure 9. Regression analysis on measured asphalt pavement density data (TransTech 2004)

Hurtley, Prowell, and Cooley (2004) of the National Center for Asphalt Technology (NCAT) studied the performances of PQI model 301 and PaveTracker by comparing their results to core density measurements. Even though neither the PQI model 301, nor the PaveTracker was recommended for quality assurance testing, the paper indicated that both instruments provided a reasonable correlation with core density measurements and that the PQI 301 demonstrated an improved relationship to core densities as compared to the PQI model 300.

Improvements in the PQI 301 model include its ability to compensate for surface water and the ability to measure density in a percent-compaction mode as well as a percent-air-voids mode. There is also a segregation mode which helps the contractor find problem areas onsite (Transtech 2002).

There have not been many research studies related to the PaveTracker. Sebesta, Scullion, and Liu of Texas Transportation Institute (TTI) studied the performance of a PaveTracker and indicated that good results using PaveTracker were observed on dense-graded mixes and not-so-good results on open-graded mixes (2005). The less acceptable results may be due to an air gap problem under the gauge. Currently, TTI is conducting another study on these devices, titled “New Technologies and Approaches to Controlling the Quality of Flexible Pavement Construction” (Wen and Bahia 2004).

The manufacturers of PQI and PaveTracker propose that their devices could be potentially used for determining differences in density at and near longitudinal joints and in areas of observed segregation. This is because paving the full width of HMA pavement in a single pass is usually impossible; therefore, most HMA pavements contain longitudinal construction joints, and differences in densities are usually observed at and near the longitudinal joints. Thus, these construction joints can often be inferior to the rest of the pavement and can eventually cause an otherwise sound pavement to deteriorate more quickly (Estakhri, Freeman, and Spiegelman 2001).

Segregation is another major cause of early deterioration of HMA pavements. When segregation appears on the surface of the pavement, the texture of the paving mixture appears more open with larger voids in the segregated areas. The result of this differential in voids is often more infiltration of air and moisture into the pavement, leading to premature raveling and potholes. Recently, the Colorado Department of Transportation conducted a research study to determine if nuclear density tests and the PQI can be used to identify segregation in asphalt pavements; the results were inconclusive. It was indicated that additional work is needed to correlate between levels of segregation and density measurements (Shuler 2005).

Sebesta, Zeig, and Scullion (2003) evaluated non-nuclear density gauges for assessing segregation, uniformity, and overall quality of HMA overlays. The research concluded that, among the non-nuclear devices evaluated, the PQI provided the most reliable estimate of differential density.

Based on their initial literature review, Wen and Bahia (2004) summarized the attributes of nuclear and non-nuclear density devices for comparison (see Table 1). It should be noted that, since the manufacturers are constantly improving the equipment, this table may not include the latest attributes of their respective devices. Some specific attributes of PQI model 301 and the PaveTracker model 2701 are summarized in Table 2 (Schmitt 2004).

Table 1. Nuclear gauge attributes for PQI and PaveTracker (Wen and Bahia 2004)

Attributes	Nuclear Density Gauge	PQI	Pavetracker
Source	Radioactive	Electromagnetic	Electromagnetic
Density Value	Absolute density value	Relative value to reference density	Relative value to reference density
Calibration	General Calibration	Calibration with cores is needed for each specific project	Calibration with cores is needed for each specific project
Measuring Depth	93% reading is affected by top 4 inches. Offer thin-layer measurement.	1-4 inches	1.75 inches
Moisture Sensitivity	Can read moisture content and not affected by moisture	Can read moisture index and correct internally.	Not affected by moisture
Temperature Sensitivity	Not affected by temperature	Can read temperature and correct internally.	Not affected by temperature
Sensitive to Aggregate Source	Not sensitive to aggregate source	Sensitive to aggregate source and offer internal correction.	Sensitive to aggregate source and offers internal correction.
Nominal Maximum Aggregate Size	Not sensitive to nominal maximum aggregate size	Sensitive to nominal maximum aggregate size and need calibration. with cores.	Sensitive to nominal maximum aggregate source and need correction
Aggregate Gradation	Not sensitive to aggregate gradation	Sensitive to aggregate gradation and offer internal correction.	Works well for fine-graded mixes, not good for coarse or gap graded mixes
Quality Control	Yes, read the density changes.	Yes, read density change	Yes, read density change
Quality Assurance	Yes, can read density value	Need calibration with core for each mix	Need calibration with core for each mix
Core Density Measurement	Can not measure the density of cores.	Can measure density of 6" diameter core	Can measure density of 6" diameter core
Repeatability	Fair	Excellent repeatability	+/-0.5 pcf
Segregation Mode	No	Yes, offer segregation mode	Yes, offer segregation mode
Cost	About $6,000	About $7,700	About $28,000
Weight	~30 lbs	16 lbs	2 lbs
Instant Measurement	Take several minutes to read	3 seconds max.	1 second
Special Training	Yes	No	No

Table 2. Attributes of PQI model 301 and PaveTracker model 2701 (Schmitt 2004)

Manufacturer	Attributes
PQI Models 300 and 301	Measures pavement density by measuring the electrical impedance of the material. Must be calibrated for the mix that is currently being measured. Many evaluations have been made on the use of PQI, but the conclusions are not consistent. The latest PQI Model 301 has the ability to compensate for surface water (could possibly manage water filler used to measure coarse surface textures).
PaveTracker Model 2701	Relative reading is offset to a representative core sample. Uses "chemical composition per unit volume" technology by measuring dielectric properties. Unlike some non-nuclear, non-mounted gauges, this model needs no moisture or temperature corrections, Very small size (3.5 inches by 4.5 inches by 2.25 inches) allows device to be taken into the lab for calibration and placed on top of a 150mm gyratory compacted specimen. The latest version of the PaveTracker is Model 2701B with dimensions of 9 inches by 16 inches by 6 inches.

In a recent study conducted for WSDOT, a field evaluation of selected non-nuclear density gauges was performed to determine their effectiveness and practicality for quality control and acceptance of asphalt pavement construction. Based on the field evaluation results, appropriate test protocols and systems of non-nuclear density devices are recommended as suitable replacements for nuclear density gauges to measure in-place asphalt pavement density (Schmitt 2005).

For the WSDOT study, preliminary data analysis was conducted for the first eight projects (out of ten). Basic statistics were computed for nuclear density gauges, non-nuclear density gauges, pavement cores, and Superpave-compacted specimens. Table 3 provides a comparison of average non-nuclear density readings with a research nuclear gauge (CPN MC-3 Serial #M391105379). Nuclear gauge readings were based on a four-minute read, and non-nuclear gauges used an average of 5 points within the nuclear density gauge base. The field study began using the CPN MC-3 nuclear gauge, PQI model 301, and PaveTracker model 2701B. The results demonstrate a consistent bias between nuclear and non-nuclear gauges and a change in bias within a project. PQI model 301 consistently read 16.2 to 20.8 pcf lower than the nuclear gauge, while PQI model 300 ranged from 9.4 to 19.9 pcf lower. PaveTracker varied from 1.8 to 13.1 pcf lower than the nuclear gauge readings (Schmitt 2005).

Table 3. Nuclear and non-nuclear gauge comparison (Schmitt 2005)

			Nuclear	Non-Nuclear Gauges			Nuclear minus Non-nuclear		
Project Index (1)	Project Name, NMAS, and Test Date (2)	Sites, n (3)	Gauge pcf (4)	PQI 301 pcf (5)	PQI 300 pcf (6)	PaveTrack. pcf (7)	PQI 301 pcf (8)	PQI 300 pcf (9)	PaveTrack. pcf (10)
1	STH 142 19mm May 12	30	147.8	127.2	---	141.2	20.6	---	6.6
1	STH 142 12.5mm June7	30	144.7	---	135.3	137.5	---	9.4	7.2
1	STH 142 12.5mm June9	20	145.9	---	130.0	139.4	---	15.9	6.5
2	STH 73 19mm, May 18	30	143.4	123.1	---	130.4	20.3	---	13.1
3	STH 64 19mm, May 20	30	144.5	122.8	---	132.5	21.8	---	12.0
4	Marsh Rd 19-mm, May 23	30	146.7	125.9	---	137.8	20.8	---	8.9
5	USH 51 19mm, May 24	30	145.3	124.9	---	138.1	20.4	---	7.2
6	IH 43 19mm, June 1	30	150.3	132.1	136.6	148.2	18.2	13.8	2.1
6	IH 43 19mm, June 2	30	148.7	132.4	137.6	146.9	16.2	11.1	1.8
7	STH 59 19mm, June 3	31	145.8	---	133.7	143.5	---	12.1	2.3
8	STH 100 19mm, June 8	32	147.0	---	127.1	139.5	---	19.9	7.5
8	STH 100 12.5mm, June8	20	145.0	---	131.6	139.0	---	13.4	6.0
8	STH 100 12.5mm, June9	20	146.4	---	133.7	138.1	---	12.7	8.3

Sargand, Kim, and Farrington (2005) provided a working review of available non-nuclear equipment for determining in-place density of asphalt, based on laboratory and field studies conducted for the Ohio Department of Transportation. The objectives of the laboratory study were to test PaveTracker performance under a variety of factors, including surface temperature, surface moisture, internal moisture, size of aggregate, sample area relative to device footprint, and measurement depth. In addition, a statistical analysis of the device's accuracy was made. The field portion of the study was designed to compare the performance of the PQI model 300 and the PaveTracker against the traditional methods at several construction sites around the state.

Based on laboratory study findings, Sargand, Kim, and Farrington (2005) reported that the performance of the PaveTracker was not significantly influenced by HMA mix surface temperature. In general, gauge readings dropped slightly with decreasing mix temperature. The PaveTracker performed better with fine mixtures than with coarse mixtures. Most notably, the presence of surface moisture significantly affected the gauge readings. With an increase in surface moisture without any internal moisture, gauge readings decreased appreciably. But with the introduction of internal moisture without the application of surface moisture, gauge readings increased. The increased amount was far larger than that resulting from core density tests. It was concluded that the results given by the PaveTracker must be interpreted carefully when moisture is present.

Based on the field study findings, Sargand, Kim, and Farrington (2005) found both the PQI and PaveTracker results to differ from both laboratory-reported core densities and nuclear density results, with statistical significance. Applying a daily mix-specific offset to gauge results as recommended by the manufacturers, hypothesis testing showed that the PaveTracker results remained statistically different from both nuclear gauge and laboratory results, but PQI results were not significantly different. Based on the results of statistical hypothesis testing, Sargand, Kim, and Farrington (2005) recommend the PQI model 300 for both quality control and quality assurance testing, provided that the manufacturer's recommendation to calibrate the device daily by applying a mix-specific offset is followed.

3.0. COLLECTION OF ELECTROMAGNETIC FIELD DATA

In the course of this research project, density measurements from field sites were collected via three methods. First, two electromagnetic gauges, a PQI and a PaveTracker, were used to obtain non-destructive density measurements. The gauges were first used at randomly selected locations. At these locations, one-foot intervals were measured and marked transversely across the paving lane. The number of measurements across a lane varied based upon the paving lane width. Gauge readings were obtained at each of these one-foot markers. On average, there were three random stations selected for each mix placed. After measurements were obtained at the random stations, measurements with the gauges were then collected at established core locations, prior to coring. Once the electromagnetic gauge measurements were recorded at core locations, coring commenced. These readings were collected at 15 sites around the state. The manufacturer's recommendations for calibrating the devices were followed in making all gauge measurements (TransTech Systems 2003; Troxler Electronics Laboratory 2003).

Table 4 summarizes information about each site incorporated in this study. There were a total of seven contractors that participated. There were three main categories of aggregate used in the mixes: limestone, slag/limestone, and quartzite. Two nominal maximum aggregate size (NMAS) categories were tested: 12.5 mm and 19.0 mm.

Table 4. Summary of field sites

Site	Paving contractor	Aggregate type	Binder content (%)	NMAS* (mm)	Traffic (ESALs)
1	1	Limestone	4.34	19.0	30,000,000
2	2	Slag/limestone	6.18	19.0	10,000,000
3	3	Quartzite	4.78	19.0	30,000,000
4	4	Limestone	5.44	12.5	1,000,000
5	4	Limestone	5.91	12.5	300,000
6	5	Limestone	5.36	12.5	1,000,000
7	6	Limestone	4.94	12.5	10,000,000
8	7	Limestone	5.85	12.5	3,000,000
9	1	Limestone	5.64	12.5	30,000,000
10	4	Limestone	5.89	12.5	3,000,000
11	4	Limestone	6.20	12.5	1,000,000
12	4	Limestone	5.88	12.5	1,000,000
13	1	Limestone	6.10	12.5	1,000,000
14	2	Slag/limestone	5.61	12.5	10,000,000
15	3	Quartzite	5.19	12.5	30,000,000

*Nominal maximum aggregate size

3.1. PaveTracker Field Density Readings Data Collection

At least three random locations were selected per paving site. At each of these random locations, readings were obtained across the width in one-foot increments. Four readings were recorded at each one-foot increment. After each reading, the device was rotated 90˚ counterclockwise for each of three subsequent readings at the same location. Figure 10 illustrates the rotational pattern adopted for collecting density readings with a PaveTracker. This rotational pattern is in accordance with the manufacturer's recommendation for obtaining density readings. The readings were obtained from between the rollers when multiple rollers were employed at a site. At two sites, readings were collected on both dry and wet surfaces. Several paving jobs have temperature data associated with each reading set.

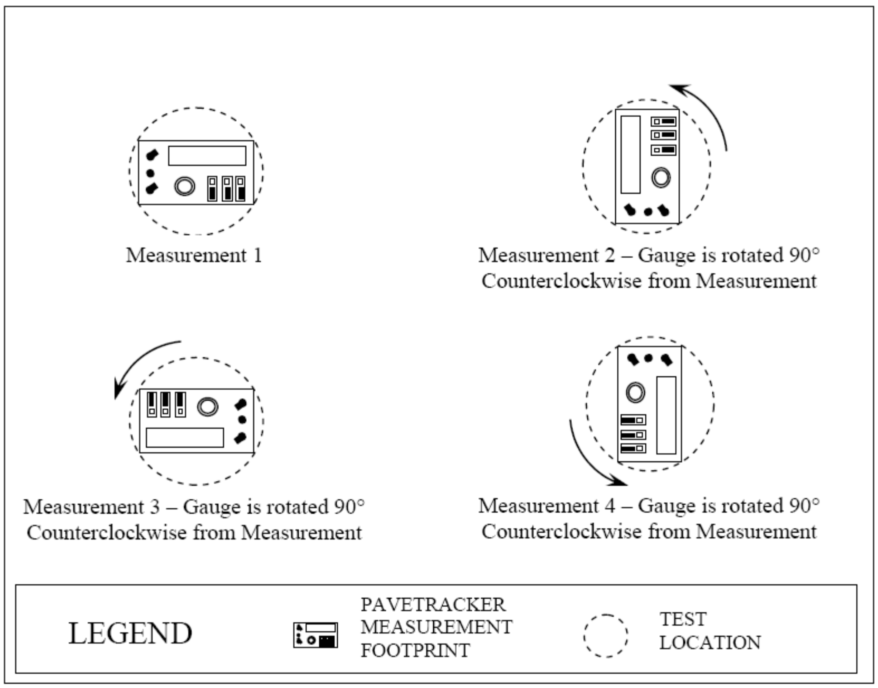

Figure 10. PaveTracker data collection pattern (New York State DOT 2003)

Once density readings were obtained from at least three randomly selected locations, density readings were obtained at the core locations. PaveTracker density readings at the core locations were centered on the core mark, and four readings were obtained by rotating the device 90˚ after each reading. It should be noted that any loose aggregate or debris was swept away prior to placing a device on a pavement.

3.2. PQI Field Density Readings

PQI density readings were obtained at one-foot intervals transversely across the width of a pavement to obtain single-mode density readings. These readings consisted of one reading at each one-foot interval transversely across the paving lane. After single-mode readings were obtained across the width of a pavement at a randomly selected station location, a randomly selected one-foot interval within the station location was identified for a multi-mode reading.

The multi-mode readings consisted of five readings in a cloverleaf pattern. First, a reading was obtained with a one-foot interval marker at the center of the PQI footprint. The second reading was obtained with the one-foot interval marker touching the lower-left edge of a PQI footprint. For the third reading, the one-foot interval marker was located at the upper-left edge of a PQI footprint. The upper-right edge of the footprint touched the one-foot interval marker for the fourth reading. The final reading was obtained with the one-foot interval marker touching the lower-right edge of the PQI footprint. Figure 11 illustrates the clover pattern followed for obtaining readings in the field in the multi-mode. The proceeding core readings were obtained in this multi-mode test process.

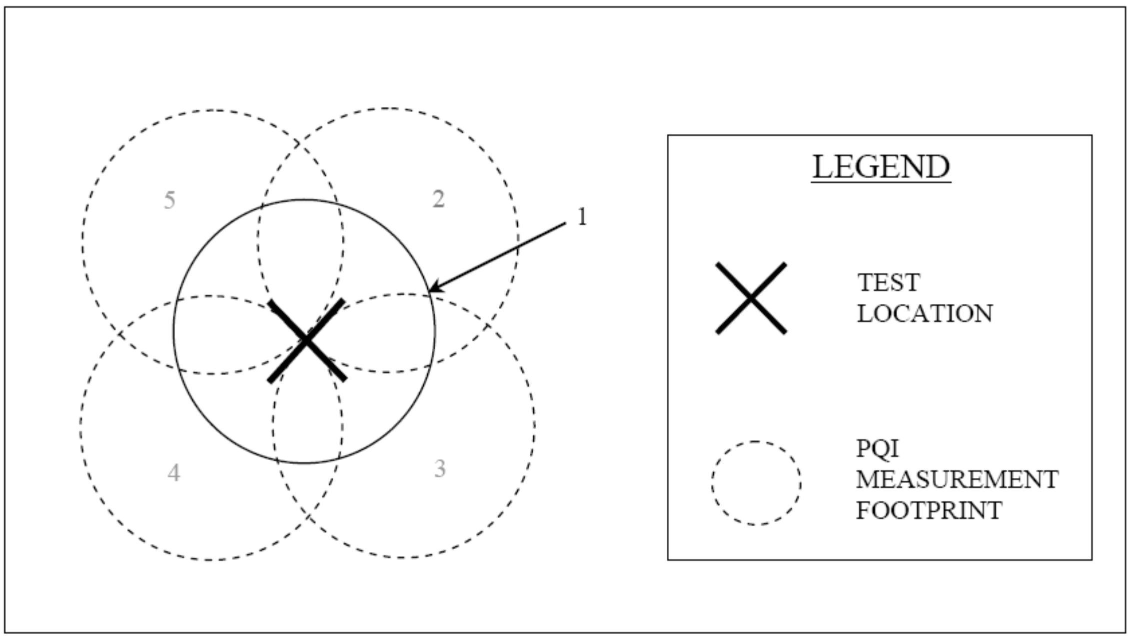

Figure 11. Schmatic layout of PQI measurement sequence (New York State DOT 2003)

3.3. Core Sample Density Readings

Core locations were selected by the Iowa DOT and were marked once paving was completed for a given day. Marking sometimes occurred the same day as paving and sometimes the following morning. Core extraction, conducted by the representative paving contractor, did not occur until both PQI and PaveTracker readings had been obtained and recorded. Cores were then transported to a contractor's field laboratory to obtain density readings following AASHTO T 166 standards. After the contractors evaluated the cores for quality control, the Iowa DOT took possession of the cores. Once both the Iowa DOT and contractor had obtained information pertinent to quality assurance, Iowa State University (ISU) took custody of the cores for additional testing. ISU also obtained the quality assurance density readings.

3.4. Statistical Analysis of Field Data

Statistical analysis of the field data consisted of analysis of variance (ANOVA), regression analysis, and mean comparisons. It should be noted that, for the field data, all analyses were imbalanced due to the nature of each individual site. The level of significance used throughout the statistical analysis was $\alpha = 0.05$.

Certain factors were given numerical values to aid in the statistical analysis. Core readings were denoted by a “0” for location. Since the final roller pass differed between sites, a reverse numbering system was employed. In other words, the final roller was assigned a “1”, the second-to-last roller was assigned a “2”, and so on. Wet pavement conditions were labeled as a “2” in regards to the condition, while dry pavements were labeled as “1.”

All joint readings were the last reading of a set. In other words, if a pavement was 14.8 feet wide, the 14th reading was the one closest to the joint.

4.0. PAVETRACKER RANDOM LOCATION STATISTICAL ANALYSIS

4.1. PaveTracker Reading Analysis

Four readings were obtained at each one-foot increment across the width of a paving lane. The orientation of the PaveTracker differed by 90˚ for each reading, with respect to the previous reading. In this section, PaveTracker readings are analyzed. The analysis consists of determining which factors significantly affect the readings and mean comparisons of those readings. A level of significance of 0.05 was employed for all analyses.

4.1.1. Significant Factors Affecting PaveTracker Readings

Identification of factors significantly affecting PaveTracker readings was conducted by evaluating the sum of squares of general linear models. Sum of squares type I (SSI) relates the significance of a factor, accounting for effects of previous factors with regards to PaveTracker readings. Sum of squares type III (SSIII) relates the significance of a factor, assuming that all other factors have been accounted for in the analysis.

Table 5 summarizes the non-continuous factors (called class variables) that significantly affect PaveTracker readings. The class variables in this case are factors that are easy to control. For example, if aggregate type is deemed statistically significant, then it can be assumed that the electromagnetic device reacts differently to various aggregates. In the table, dot in a cell indicates a factor that is deemed statistically significant.

The analysis indicates that the device is sensitive both to changes in density after roller passes and at different locations along a paving lane. The variables deemed significant for SSI and SSIII are dissimilar for all but roller pass. It is evident from the analysis that roller pass has a significant effect on PaveTracker readings. Deeming ‘roller pass’ a statistically significant class variable for PaveTracker readings indicates that a PaveTracker device is sensitive to changes in density after a roller pass. A device sensitive to density changes after a roller pass bodes well for implementation, as density generally increases after an added roller pass.

Table 5. Significant factors affecting PaveTracker readings

Source	SSI	SSIII
Site	•	
Station		•
Pavement Width		•
Pavement Condition		
Contractor		
Aggregate Type		
NMAS		
Traffic Level		
Roller	•	•
Distance Across Pavement Width		

A regression model was evaluated to account for the class variables and continuous variables. A regression model can not only evaluate which variables are significant but also the nature of the relationship between factors. Table 6 summarizes the parameter estimates and significance associated with each variable. The parameter estimates in the table were generated using regression analysis. If a level of significance of 0.05 was applied to the results, the variables deemed significant would be the station, pavement condition (i.e., wet or dry), contractor, aggregate (i.e., quartzite, slag/limestone, or limestone), binder content, NMAS, and roller pass.

Table 6. Regression analysis of PaveTracker random location readings

Variable	Paramter Estimates	Pr > |t|
Intercept	155.83878	<.0001
Site	-0.10602	0.4913
Station	1.10806	0.0369
Pavement Width	0.03274	0.8469
Pavement Condition	-13.08398	0.0237
Contractor	-1.56077	<.0001
Aggregate	-6.38087	<.0001
Binder Content	7.38617	0.0017
NMAS	-1.68917	<.0001
Traffic Level	-1.56E-07	0.2021
Roller Pass	-4.53788	<.0001
Distance Across Pavement Width	0.07371	0.4830

4.1.2. Mean Comparisons Using Tukey's Method

Several mean comparisons were employed to evaluate which classification variable levels were significantly different. The categories evaluated were site (15 levels), condition (2 levels), contractor (7 levels), NMAS (2 levels), traffic level (5 levels), aggregate type (3 levels), and roller pass (3 levels).

Table 7 summarizes the sites deemed statistically significantly different. It can be seen that there are three sites that are significantly different than the majority of sites—sites 7, 13, and 15:

- The readings from site 7 may have differed from the other sites because it rained between the paving and coring times. However, one other site also endured rain between the paving and coring times, site 3. Site 3 was exposed to a more severe rainstorm than site 7. If rain was the sole cause of the difference, then site 3 should also have differed significantly from the majority of sites. This discrepancy indicates that a factor other than rain affected the PaveTracker readings from site 7. Subsequent analysis of data from site 7 indicates that segregation was likely an issue.
- Site 13 is a low-volume site with a failing subgrade. The poor subgrade could be affecting the PaveTracker readings for site 13. However, information about subgrade conditions for other sites is not available and, thus, whether another site with a poor subgrade was contained in the study is unknown.
- Site 15 contained slag, which likely altered the readings due to a high residual metal content.

Table 7. Mean comparison by site

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	■						•			•			•		•
2		■					•								
3			■				•						•		•
4				■											
5					■		•						•		•
6						■	•								•
7	•	•	•		•	•	■	•	•	•	•	•	•	•	•
8							•	■			•			•	•
9							•		■				•		•
10	•						•			■	•			•	
11							•	•		•	■		•		•
12							•					■	•		•
13	•		•		•		•		•		•	•	■	•	
14							•	•		•			•	■	•
15	•		•		•	•	•	•	•		•	•		•	■

The next factor evaluated was pavement condition. PaveTracker readings were obtained from both dry and wet pavements. The pavements were moistened by pouring approximately 10 oz. of bottled water on a pavement prior to using a PaveTracker. The mean comparison indicated that there is a significant statistical difference between readings obtained from the same location under wet and dry conditions. Further examination of whether or not either condition could make the difference regarding acceptable or unacceptable density readings will be addressed in a future section of this report.

The mixes collected for this study were obtained from seven different contractors. Table 8 summarizes the results of comparing PaveTracker readings between contractors. From the table, it can be seen that contractor 6 yielded significantly different PaveTracker results than all of the other contractors. Only one site paved by contractor 6 was evaluated. If more sites paved by contractor 6 were evaluated, the contractor might not have differed significantly from the others. Contractor 2 also differed from a considerable number of contractors (contractors 1, 3, 4, and 6). Contractor 2 produced a slag mix that resulted in significantly different results than those obtained from other sites. It is hypothesized that slag in a mix can alter the results of electromagnetic gauges.

Table 8. Mean comparison by contractor

Contractor	1	2	3	4	5	6	7
1	■	•				•	
2	•	■	•	•		•	
3		•	■			•	
4		•		■		•	
5					■	•	
6	•	•	•	•	•	■	•
7						•	■

Comparisons between the three different aggregate types indicated that mixes with slag resulted in significantly different PaveTracker readings. The quartzite and limestone mixes do not appear to have resulted in significantly different PaveTracker readings. Table 9 summarizes the mean comparisons of significance.

Table 9. Mean comparison by aggregate type

Aggregate	Quartzite	Slag/Limestone	Limestone
Quartzite	■	•	
Slag/Limestone	•	■	•
Limestone		•	■

The determined significance of other variables is as follows:

- The mean comparison between the two NMASs used indicated that the PaveTracker readings from the two respective groups could not be considered statistically different. Further investigation into the gradation of the mixes should be conducted to determine which gradations are causing the differences.
- All of the traffic levels differed from one another.
- The sets of PaveTracker data grouped by roller pass were all deemed statistically different.

- An additional analysis was conducted to compare end readings to inner readings across the width of a pavement. The analysis indicated that the end readings differed from the inner readings.

4.1.3. Correlation Analysis

Correlation analysis revealed strong relationships between different variables. Table 10 relates Pearson Correlation Coefficients for variables associated with PaveTracker readings from random field locations. The variables which exhibited a slightly strong (greater than ±0.60) relationship were traffic level–aggregate type, and traffic level–binder content.

Table 10. Correlation matrix for PaveTracker random location readings

	Site	Station	Condition	Aggregate Type	NMAS	Traffic Level	Roller Pass	Distance Across Pavement	Binder Content	Width
Site		-0.05146	-0.0463	-0.13562	0.16588	-0.37531	-0.06453	-0.02185	0.49662	-0.07639
Station	-0.05146		0.06276	-0.0193	0.14492	-0.04014	0.04642	-0.06146	0.02016	-0.14848
Condition	-0.0463	0.06276		0.01303	0.06808	-0.03433	0.00718	0.04116	-0.01436	-0.03969
Aggregate Type	-0.13562	-0.0193	0.01303		-0.46375	-0.65633	-0.02861	0.18519	0.17641	0.39085
NMAS	0.16588	0.14492	0.06808	-0.46375		0.21994	-0.07298	-0.01545	-0.01041	-0.39232
Traffic Level	-0.37531	-0.04014	-0.03433	-0.65633	0.21994		0.12083	0.02212	-0.60869	0.09182
Roller Pass	-0.06453	0.04642	0.00718	-0.02861	-0.07298	0.12083		-0.02018	-0.17321	-0.05864
Distance Across Pavement	-0.02185	-0.06146	0.04116	0.18519	-0.01545	0.02212	-0.02018		-0.109	0.43081
Binder Content	0.49662	0.02016	-0.01436	0.17641	-0.01041	-0.60869	-0.17321	-0.109		-0.23846
Width	-0.07639	-0.14848	-0.03969	0.39085	-0.39232	0.09182	-0.05864	0.43081	-0.23846	

4.2. PaveTracker Conclusions

The PaveTracker device was used in the field at both random and core locations. Analysis was conducted to determine which factors significantly affected PaveTracker readings in the field. Roller pass was deemed statistically significant, which indicates that the PaveTracker device is sensitive to density changes caused by roller passes. The regression analysis further implied that the pavement condition (i.e., wet or dry), contractor, aggregate type, NMAS, traffic level, and roller pass were all significant variables affecting PaveTracker density readings.

The two sites that varied the most from the other PaveTracker data collection locations were sites 7 and 15. Mean comparisons revealed that there are significant differences between wet density readings and dry density readings, as well as at different traffic levels and between subsequent roller passes. Mixes with slag also appear to be statistically different than those without slag. The 19.0-mm and 12.5-mm NMAS mixes were not found to be statistically different.

Correlation analysis revealed that there are slightly strong relationships: traffic level–aggregate type, and traffic level–binder content. The analysis indicates that the PaveTracker is sensitive to density changes and further research should be conducted to evaluate the areas of difference and establish guidelines for use in Iowa.

5.0. PQI RANDOM LOCATION STATISTICAL ANALYSIS

5.1. Single-Mode PQI Reading Analysis

The first set of PQI readings was obtained in single mode, meaning that only one reading was collected at each location. The readings were obtained at one-foot intervals across the width of a paving lane. The following sections summarize statistical analyses conducted on PQI single-mode readings.

5.1.1. Significant Factors Affecting Single-Mode PQI Readings

Identification of factors significantly affecting a PQI reading was conducted by evaluating the sum of squares of general linear models SSI and SSIII—just as it was done for PaveTracker analysis. Table 11 summarizes the class variables deemed significant. It can be seen that not only is a PQI in single mode sensitive to changes in density between roller pass; it is also sensitive to density changes across the width of a pavement. The density across a pavement can vary, which a PQI seems adept at detecting.

Table 11. Factors significantly affecting single-mode PQI readings

Source	SSI	SSIII
Site	•	
Station	•	•
Pavement Width		
Contractor		
Aggregate Type		
NMAS		
Traffic Level		
Roller	•	•
Distance Across Pavement Width	•	•

A regression model was evaluated to account for the class variables and continuous variables. A regression model can not only evaluate which variables are significant but also the nature of the relationship between factors. Table 12 summarizes the regression analysis conducted to determine the significant factors (both class and continuous variables) and the nature of a factor's relationship with the regression model. Using a level of significance of 0.05, the variables deemed statistically significant are station location, pavement width, distance across pavement width at which the reading was obtained (i.e., transverse location, and pavement temperature). It should be noted that site and NMAS were close to being deemed statistically significant factors as well. Additional testing could alter the labeling of site and NMAS as not statistically significant variables.

A comparison between PQI core readings and random locations for sites with temperature data was performed. The analysis indicated that there is no statistical difference between the final readings and the core readings. Statistical comparisons between the two outer readings (those closest to the shoulder and joint, respectively) and the inner final readings (all readings except the two outermost) were conducted, and in all cases the outer readings differed from the inner readings.

Table 12. Regression analysis of factors affecting single-mode PQI readings

Variable	Parameter Estimate	Pr > |t|
Intercept	125.21586	0.0049
Site	-0.67661	0.0676
Contractor	2.68108	0.1471
Aggregate	-1.02782	0.661
Binder Content	5.9159	0.2058
NMAS	-0.81495	0.0595
Traffic Level	3.73E-07	0.0909
Station	1.57909	0.0024
Width	0.98876	0.0431
Roller Pass	-0.86985	0.4475
Distance Across Pavement	0.2423	0.0166
Temperature	-0.06728	0.0016

5.1.2. Mean Comparisons of Single-Mode PQI Readings Using Tukey's Method

Several mean comparisons were employed to evaluate which classification variable levels were significantly different. The categories evaluated were site (15 levels), contractor (7 levels), NMAS (2 levels), traffic level (5 levels), aggregate type (3 levels), and roller pass (3 levels). It should be noted that pavement condition was not considered, since no wet pavement readings were obtained in the single mode using a PQI. All of the wet pavement readings taken with a PQI occurred in multi mode. In the tables summarizing results of mean comparisons, significant differences between groups are indicated by a solid black dot. A level of significance of 0.05 was employed for all comparisons.

Table 13 summarizes the results of mean comparisons of single-mode PQI readings grouped by site. There are four sites that significantly differ from all other sites—sites 2, 7, 8, and 15. Table 14 summarizes the results of mean comparisons grouped by contractor. It appears that there are significant differences between almost all contractors. This is interesting, since not all of the mixes were deemed statistically different. Table 15 summarizes mean comparison results grouped by aggregate type. Mixes with slag were found to differ significantly from limestone or quartzite mixes. Table 16 summarizes the mean comparisons of single-mode PQI readings by traffic level. It can be seen that there are significant differences between most of the traffic levels.

Table 13. Mean comparisons of single-mode PQI readings by site

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	■	•	•			•	•	•							•
2	•	■	•	•	•	•	•	•	•	•	•	•	•	•	•
3	•	•	■				•	•	•	•	•	•		•	•
4		•		■			•	•						•	•
5		•			■		•	•		•					•
6	•	•				■	•	•	•	•	•	•		•	•
7	•	•	•	•	•	•	■	•	•	•	•	•	•	•	•
8	•	•	•	•	•	•	•	■	•	•	•	•	•	•	•
9		•	•			•	•	•	■	•					•
10		•	•		•	•	•	•	•	■			•		•
11		•	•			•	•	•			■				•
12		•	•			•	•	•				■			•
13		•					•	•		•			■	•	•
14		•	•		•	•	•	•					•	■	•
15	•	•	•		•		•	•	•	•	•	•		•	■

Table 14. Mean comparisons of single-mode PQI readings by contractor

Contractor	1	2	3	4	5	6	7
1	■	•	•		•	•	•
2	•	■	•	•	•	•	•
3	•	•	■	•		•	•
4		•	•	■	•	•	•
5	•	•		•	■	•	•
6	•	•	•	•	•	■	•
7	•	•	•	•	•	•	■

Table 15. Mean comparisons of single-mode PQI readings by aggregate type

Aggregate	Quartzite	Slag/Limestone	Limestone
Quartzite	■	•	
Slag/Limestone	•	■	•
Limestone		•	■

Table 16. Mean comparisons of single-mode PQI readings by traffic level

Traffic Level	300000	1000000	3000000	10000000	30000000
300000	■	•	•	•	
1000000	•	■	•		•
3000000	•	•	■	•	•
10000000	•		•	■	•
30000000		•	•	•	■

In regards to other variables, comparisons between 12.5-mm and 19.0-mm NMAS mixes indicate that the means cannot be deemed statistically different. In other words, the density readings for 12.5-mm and 19.0-mm NMAS were relatively similar, without significant differences in readings. Readings obtained from the randomly selected stations also could not be deemed statistically different, with the exception of station 5. However, there was only one site that had five randomly selected stations and, thus, more random station readings may yield different results or reveal this result to be an anomaly. Density readings grouped by roller pass were all found significantly different. Significant statistical differences between roller pass groupings indicate that a PQI in the single mode is sensitive to density changes after each roller pass.

5.1.3. Correlation Analysis of Factors Affecting Single-Mode PQI Readings

Correlation analysis revealed strong relationships between some of the variables. Table 17 relates Pearson Correlation Coefficients for variables associated with PQI single-mode readings from random field locations. The factors that appear to have a correlation value that is slightly strong (greater than ±0.60) are binder content–site, and traffic level–contractor.

Table 17. Correlation matrix based on single-mode PQI random location readings

	Site	Contractor	Aggregate Type	Binder Content	NMAS	Traffic Level	Station	Width	Roller Pass	Distance Across Pavement	Temperature
Site		0.10044	-0.44043	0.61816	-0.40748	-0.34728	-0.05536	-0.08283	-0.12503	-0.01592	0.17721
Contractor	0.10044		0.12423	0.05742	-0.48015	-0.61261	-0.07624	-0.12791	0.08754	-0.0336	-0.55229
Aggregate Type	-0.44043	0.12423		-0.01796	-0.46019	-0.24652	-0.04372	0.26641	0.068	0.08796	-0.07461
Binder Content	0.61816	0.05742	-0.01796		-0.51345	-0.5747	0.05532	-0.34916	-0.21586	-0.14776	-0.1441
NMAS	-0.40748	-0.48015	-0.46019	-0.51345		0.57711	0.06093	0.08286	0.06631	0.03983	0.20571
Traffic Level	-0.34728	-0.61261	-0.24652	-0.5747	0.57711		0.01451	0.03622	0.08611	-0.00558	0.35095
Station	-0.05536	-0.07624	-0.04372	0.05532	0.06093	0.01451		-0.20255	0.02236	-0.08059	0.1189
Width	-0.08283	-0.12791	0.26641	-0.34916	0.08286	0.03622	-0.20255		-0.01124	0.43067	0.11388
Roller Pass	-0.12503	0.08754	0.068	-0.21586	0.06631	0.08611	0.02236	-0.01124		-0.02445	0.53916
Distance Across Pavement	-0.01592	-0.0336	0.08796	-0.14776	0.03983	-0.00558	-0.08059	0.43067	-0.02445		0.03369
Temperature	0.17721	-0.55229	-0.07461	-0.1441	0.20571	0.35095	0.1189	0.11388	0.53916	0.03369	

5.2. Random PQI Five-Reading Analysis

Another method of obtaining density readings using a PQI is to collect multiple readings in a cloverleaf pattern instead of one single reading. The multiple-readings method will be referred to as 'multi mode.' For the multi mode, an initial reading is obtained and four additional readings are collected at the four corners of the initial reading. These multi-mode readings were only collected at randomly selected locations, one per station. The following analysis relates factors affecting multi-mode PQI readings.

5.2.1. Significant Factors Affecting Multi-Mode PQI Readings

As with single-mode readings, analysis was conducted to see which of the class factors accounted for were significantly affecting multi-mode PQI readings. Table 18 summarizes which factors were deemed statistically significant. A dot in a cell indicates that a factor is significant. Both sum of squares type I and III revealed that station location, roller pass, and distance across the pavement width were all significant. This would imply that the PQI in multi mode is sensitive to changes in density caused by a roller pass and those caused a change in transverse location.

Table 18. Significant factors affecting multi-mode PQI readings obtained at random locations

Source	SSI	SSIII
Site	•	
Station	•	•
Pavement Width		
Pavement Condition	•	
Contractor		
Aggregate Type		
NMAS		
Traffic Level		
Roller	•	•
Distance Across Pavement Width	•	•

Table 19 summarizes the results of regression analysis. Regression analysis evaluates the significance and relationship nature of a variable. Using a level of significance α = 0.05, the analysis indicates that site, pavement width, contractor, aggregate type, binder content, roller pass, and distance across pavement are all significant factors.

Table 19. Regression analysis of multi-mode PQI readings

Variable	Parameter Estimate	Pr > |t|
Intercept	152.79259	<.0001
Site	1.72543	<.0001
Station	-0.54766	0.3012
Width	-0.50271	0.0082
Condition	2.22136	0.233
Contractor	-2.67693	<.0001
Aggregate Type	10.33595	<.0001
Binder Content	-3.98782	0.0287
NMAS	0.57366	0.2228
Traffic Level	1.45E-07	0.0541
Roller Pass	-4.88213	<.0001
Distance Across Pavement	-0.89696	<.0001

5.2.2. Mean Comparisons of Multi-Mode PQI Readings

Mean comparisons using Tukey's method were conducted to determine if there are significant differences between the variable levels. The comparisons considered were site, contractor, aggregate type, NMAS, and roller pass. Table 20 summarizes the results of mean comparisons conducted on the data, grouped by site. There are four sites that differ from the majority—if not all—of the other sites: sites 2, 7, 12, and 15.

Table 20. Summary of mean multi-mode PQI readings by site

Site	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	■	•					•	•				•			•
2	•	■	•	•	•	•	•	•	•	•	•	•	•	•	•
3		•	■				•					•			•
4		•		■			•								
5		•			■		•	•				•			•
6		•				■	•	•			•			•	
7	•	•	•	•	•	•	■	•	•	•	•	•	•	•	•
8	•	•			•	•	•	■	•	•		•			•
9		•					•	•	■			•		•	
10		•					•	•		■		•		•	•
11		•				•	•				■	•			•
12	•	•	•		•		•	•	•	•	•	■	•	•	
13		•					•					•	■		•
14		•				•	•		•	•		•		■	•
15	•	•	•		•		•	•		•	•		•	•	■

Table 21 summarizes the results of mean comparisons of PQI multi-mode readings by contractor. Three contractors differ significantly from the others: contractors 2, 6, and 7. Contractor 2 supplied mixes with slag; this could account for its variance from the other contractors, who did not use slag in their mixes.

Table 21. Summary of mean multi-mode PQI readings by contractor

Contractor	1	2	3	4	5	6	7
1	■	•				•	•
2	•	■	•	•	•	•	•
3		•	■			•	•
4		•		■		•	•
5		•			■	•	•
6	•	•	•	•	•	■	•
7	•	•	•	•	•	•	■

Comparisons between NMASs (12.5-mm versus 19.0-mm) did not indicate that there is a significant difference between the two groups. Grouping by pavement condition did however yield a significant difference between dry and wet pavements. Comparisons between roller passes indicated that the only roller passes that were not deemed statistically different were the final and next-to-last passes. Comparisons between aggregate type (i.e., quartzite, slag/limestone, and limestone) did not yield any significant differences.

5.2.3. Correlation Analysis of Factors Affecting Multi-Mode PQI Readings

Pearson's Correlation Coefficients were calculated to determine which factors may be related (see Table 22). The aggregate type–NMAS relationship was determined to be somewhat strong. This, however, could be somewhat misleading, since the majority of mixes were predominantly limestone.

Table 22. Pearson's Correlation Coefficients for multi-mode PQI readings

	Site	Station	Width	Condition	Contractor	Aggregate	Binder Content	NMAS	Traffic Level	Roller Pass	Distance Across Pavement
Site		-0.13632	0.19739	-0.24584	0.0729	-0.2318	0.36674	-0.39767	-0.12025	0.03874	-0.04531
Station	-0.13632		-0.32646	0.15576	-0.11549	-0.12472	0.1058	0.18997	0.01587	-0.0015	-0.05933
Width	0.19739	-0.32646		-0.1818	0.00953	0.35287	-0.36899	-0.25472	0.03107	0.01761	0.56461
Condition	-0.24584	0.15576	-0.1818		0.16201	0.02331	0.08895	0	-0.24293	-0.15534	0.11154
Contractor	0.0729	-0.11549	0.00953	0.16201		0.17804	-0.14665	-0.41413	-0.50795	0.12998	0.10798
Aggregate	-0.2318	-0.12472	0.35287	0.02331	0.17804		-0.04428	-0.65204	-0.2154	0.11014	0.15385
Binder Content	0.36674	0.1058	-0.36899	0.08895	-0.14665	-0.04428		-0.21871	-0.51009	-0.15566	-0.39734
NMAS	-0.39767	0.18997	-0.25472	0	-0.41413	-0.65204	-0.21871		0.34155	-0.08929	-0.04966
Traffic Level	-0.12025	0.01587	0.03107	-0.24293	-0.50795	-0.2154	-0.51009	0.34155		0.12766	0.02308
Roller Pass	0.03874	-0.0015	0.01761	-0.15534	0.12998	0.11014	-0.15566	-0.08929	0.12766		-0.01031
Distance Across Pavement	-0.04531	-0.05933	0.56461	0.11154	0.10798	0.15385	-0.39734	-0.04966	0.02308	-0.01031	

5.3. Comparison between Single-Mode and Multi-Mode PQI Readings

As mentioned, two types of readings were obtained when using a PQI: single-mode and multi-mode readings. This section summarizes the statistical similarities and differences between the two modes. First, a comparison of the variables significantly affecting the different modes will be explored, followed by identifying if the same differences between levels within a factor were realized by both modes.

When comparing class variables, both modes identified site, station location, roller pass, and distance across pavement width as variables that significantly affected PQI readings. In multi mode, pavement condition was also identified as significant; however, this is not relevant for comparison with single-mode results, since no wet pavement readings were obtained in single mode. Regression analysis of both data types indicated that station location, pavement width, and distance across (transverse location of the reading) are all factors significantly affecting density readings. Using the multi-mode data, however, other factors were also deemed statistically significant; those factors were site, aggregate type, and binder content.

Mean comparisons of both data sets found several differences between factor levels. Both modes identified sites 2, 7, and 15 as significantly different than other sites. However, both modes identified additional sites as significantly different—sites that were not the same for both modes. In single mode, almost all readings grouped by contractor were deemed statistically different, while multi-mode analysis indicated that only contractors

2, 6, and 7 were statistically different than the others. Interestingly, single-mode reading analysis detected significant differences between mixes with slag and those without; this finding contrasts with multi-mode results, which indicated no such differences. No statistical differences were revealed between NMAS groups for single mode, but differences were detected for multi-mode readings. There was no agreement between correlation results for the two modes.

There are some similarities between single- and multi-mode PQI readings. The differences can be most likely attributed to a limited dataset for single-mode operation. Small differences in single-mode readings could have greatly affected the results, since the dataset was relatively small compared to the multi-mode dataset. Based on the statistical analysis and observations in the field, the multi mode is recommended for quality assurance testing. However, the single mode appears to be adequate for quality control measurements (assuming that these readings will occur more frequently along the length of a pavement).

5.4. PQI Conclusions

Two methods for collecting PQI density readings were employed: single mode and multi mode. For the single mode, evaluations of class variables indicated that station, roller pass, and distance across pavement width significantly affected PQI results. The regression analysis of the single-mode data revealed that station, pavement width, distance across pavement width, and temperature were significant factors. The four sites found to have significantly different results than the other sites, according to the single-mode data, were sites 2, 7, 8, and 15. The majority of contractor comparisons were deemed statistically significant when evaluating the single-mode data. Slag was also found to significantly affect the readings.

Multi-mode data evaluations also found the following class variables to be significant: station, roller pass, and distance across pavement width. Regression analysis of multi-mode data revealed that site, station, pavement width, contractor, aggregate type, binder content, roller pass, and distance across pavement width were significant variables. Mean comparisons revealed that four sites differed significantly when comparing multi-mode data: sites 2, 7, 12, and 15. Like the single-mode PQI data, comparisons of contractors resulted in almost all pairings being deemed significant. However, unlike the single-mode PQI data, the multi-mode data evaluations did not find aggregate type to be significant.

6.0. ANALYSIS OF CORE READINGS

6.1. Statistical Analysis of Core Densities

Density readings were obtained at core locations prior to coring, using both a PQI and PaveTracker. In this section, density readings collected using a PaveTracker and PQI were compared to density measures of cut cores. The analysis includes an evaluation of all the data and the individual sites.

Comparisons between core density measurements, PaveTracker readings, and PQI readings of all ungrouped data indicated that all three methods are statistically different. The level of significance used for the evaluations was 0.05.

Comparisons within a site revealed some similarities and patterns. Table 23 summarizes the mean density readings. In most cases, PaveTracker density readings were lower than both core and PQI densities. Core sample densities tended to be in between PaveTracker and PQI densities. Table 24 lists the coefficients of variation (reported as a percentage) for core samples, PaveTracker, and PQI densities. PQI densities tended to be much more variable than both core samples and PaveTracker readings. In most cases, the core sample densities were less variable. Significant comparisons are documented in Table 25, indicated with a solid black dot. Most of the mean comparisons resulted in being labeled significantly different. No cores were collected for site 4; therefore, “N/A” (not available) is listed in the core density cells for both Table 23 and Table 24.

Table 23. Summary of mean density readings at core locations by site

Site	Core Density (g/cm^3)	PaveTracker		PQI	
		Reading (g/cm^3)	Density Correction Factor	Reading (g/cm^3)	Density Correction Factor
1	2.33	2.14	1.09	2.41	0.97
2	2.22	2.11	1.05	2.31	0.96
3	2.31	2.12	1.09	2.44	0.95
4	N/A	2.15	N/A	2.48	N/A
5	2.26	2.15	1.05	2.62	0.86
6	2.29	1.84	1.24	2.13	1.08
7	2.29	2.22	1.03	2.57	0.89
8	2.34	2.17	1.08	2.60	0.90
9	2.32	2.16	1.07	2.52	0.92
10	2.26	2.17	1.04	2.43	0.93
11	2.26	2.08	1.09	2.42	0.93
12	2.26	2.13	1.06	2.36	0.96
13	2.26	2.28	0.99	2.52	0.90
14	2.37	2.37	1.00	2.65	0.89
15	2.33	2.09	1.11	2.50	0.93

Table 24. Summary of coefficient of variations of density readings by site

Site	Core Density COV (g/cm^3)	PaveTracker Reading COV (g/cm^3)	PQI Reading COV (g/cm^3)
1	1.30	2.39	5.18
2	1.03	1.87	5.13
3	1.15	1.97	5.46
4	N/A	1.22	5.68
5	0.46	1.56	4.49
6	0.68	0.89	18.45
7	0.68	1.36	4.49
8	0.96	2.43	2.59
9	1.53	2.36	3.93
10	0.67	1.65	4.02
11	0.96	2.08	6.42
12	0.66	1.33	6.10
13	0.97	0.90	0.10
14	0.86	1.76	5.13
15	1.45	1.27	3.78

Table 25. Summary of mean comparisons by site

Site	Cores vs. PQI	Cores vs. Pavetracker	Pavetracker vs. PQI
1		●	●
2	●	●	●
3	●	●	●
4	N/A	N/A	●
5	●	●	●
6		●	●
7	●		●
8	●	●	●
9	●	●	●
10	●	●	●
11	●	●	●
12	●	●	●
13	●	●	●
14	●		●
15	●	●	●

The analysis above indicates that there are differences between the three methods of evaluating pavement density. However, the differences do not necessarily indicate that payment to contractors would be affected. The first set of payment adjustments based on quality indices were for unadjusted data collected in the field. The second set was based on adjusted field data. Table 26 lists the quality indices calculated using densities from all three methods. Table 27 summarizes payments for each site, based on densities. It appears that if payment were based on PaveTracker readings, many of the contractors who received full payment would be penalized. All but one of the PQI readings coincide with the payment level based on extracted cores.

Table 26. Quality indices

Site	PaveTracker	PQI	Cores
1	-2.08	1.38	2.50
2	-5.26	-0.13	0.98
3	-1.98	2.66	1.75
4	1.95	2.68	N/A
5	-2.59	1.75	3.84
6	-3.18	3.11	0.68
7	-24.69	-0.30	2.68
8	0.35	3.06	5.11
9	-2.14	4.61	2.38
10	-1.66	2.08	2.60
11	-2.40	1.50	3.39
12	-2.68	0.99	3.57
13	2.72	2.46	N/A
14	1.67	3.28	1.79
15	-6.25	2.56	2.25

Table 27. Payment amount based on densities

Site	PaveTracker	PQI	Cores
1	Max. 75%	100%	100%
2	Max. 75%	Max. 75%	100%
3	Max. 75%	100%	100%
4	100%	100%	N/A
5	Max. 75%	100%	100%
6	Max. 75%	100%	95%
7	Max. 75%	Max. 75%	100%
8	85%	100%	100%
9	Max. 75%	100%	100%
10	Max. 75%	100%	100%
11	Max. 75%	100%	100%
12	Max. 75%	100%	100%
13	100%	100%	N/A
14	100%	100%	100%
15	Max. 75%	100%	100%

Since there are some discrepancies between the two electromagnetic gauges and extracted cores, correction factors were calculated for each gauge and site. The correction factors were then multiplied by the raw data readings to obtain an adjusted data set. Quality indices were calculated based on the adjusted data set. Table 28 lists the calculated adjusted quality indices. Table 29 summarizes the amount of payment a contractor would receive if quality assurance was based on the adjusted dataset. Interestingly, PaveTracker readings coincide with core data for all sites except one, while PQI readings differ from core data for seven sites. Conversely, the PQI readings corresponded better with the core readings prior to the application of a correction factor. Figure 12 graphically displays the relationship between the actual density readings and the adjusted density readings.

Table 28. Adjusted density quality indices

Site	PaveTracker	PQI
1	1.65	0.76
2	-2.73	-0.87
3	1.12	0.67
4	N/A	N/A
5	3.75	0.79
6	0.18	4.06
7	1.98	0.10
8	2.44	0.74
9	0.92	0.86
10	1.05	0.43
11	1.58	0.51
12	1.82	0.30
13	1.90	0.46
14	3.98	1.37
15	2.24	0.75

Table 29. Payment based on adjusted density

Site	PaveTracker	PQI	Cores
1	100%	100%	100%
2	Max. 75%	Max. 75%	100%
3	100%	100%	100%
4	N/A	N/A	N/A
5	100%	100%	95%
6	85%	100%	100%
7	100%	85%	100%
8	100%	100%	100%
9	100%	100%	100%
10	100%	95%	100%
11	100%	95%	100%
12	100%	95%	100%
13	100%	95%	N/A
14	100%	100%	100%
15	100%	100%	100%

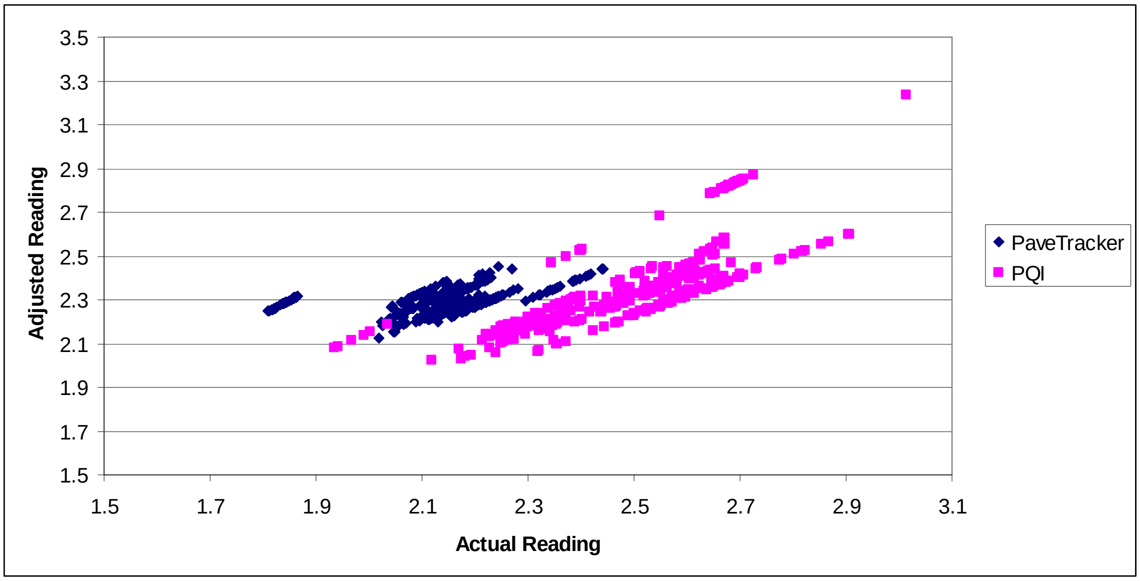

Figure 12. Comparison between actual and adjusted core readings

6.2. Graphical Analysis of Core Densities

Graphs illustrating the dispersion of density readings were constructed. Figure 13 illustrates the dispersion for all of the sites encompassed in the study. It was observed that densities obtained using a PQI were more variable than either those obtained using a PaveTracker or using extracted cores. PQI density readings tended to be greater than those obtained from the other two methods. Sites 1 and 7 exhibited readings consistent with segregation issues.

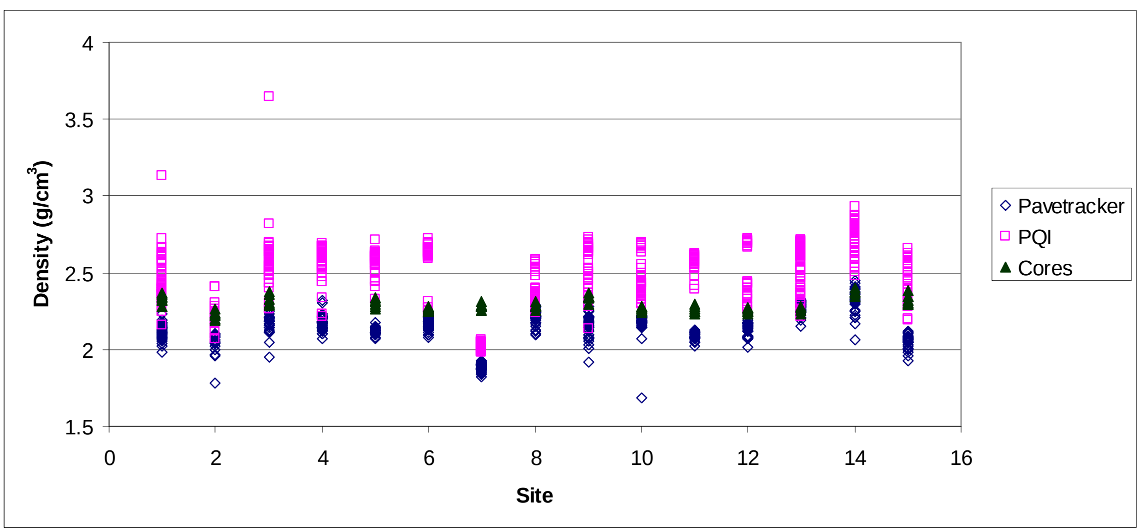

Figure 13. Density readings at core locations

Figures 14 through 28 depict density readings obtained at each site after the final roller pass. These readings reveal where some of the variability occurs when evaluating quality assurance density readings; density readings tend to change across the width of a pavement. Changes in density across the width of a pavement could be attributed to roller patterns and/or subgrade issues. Since these are graphs of densities obtained after final roller patterns, any of these readings could hypothetically be employed in determining quality assurance densities for a paving job.

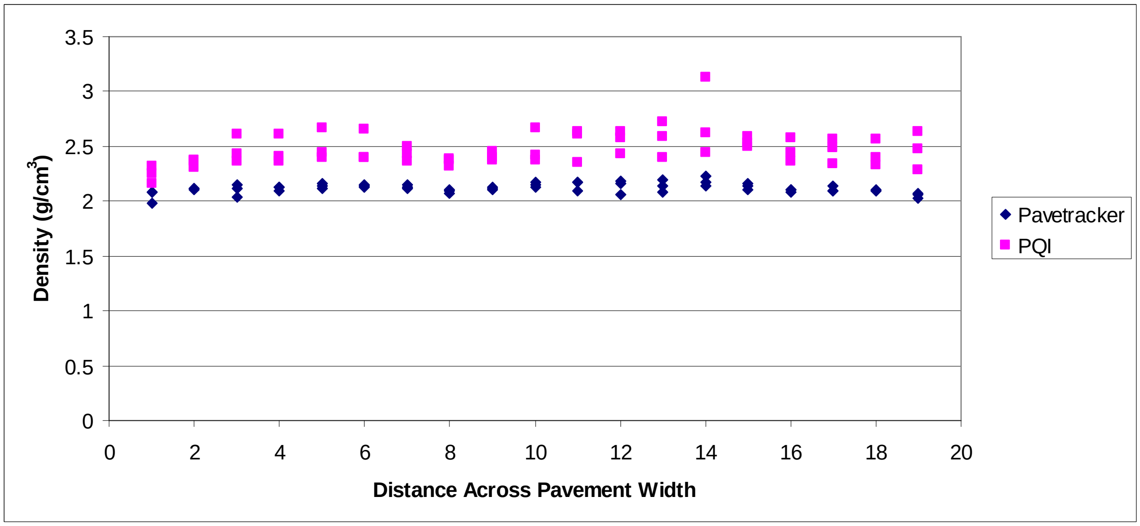

Figure 14. Site 1 final roller density readings

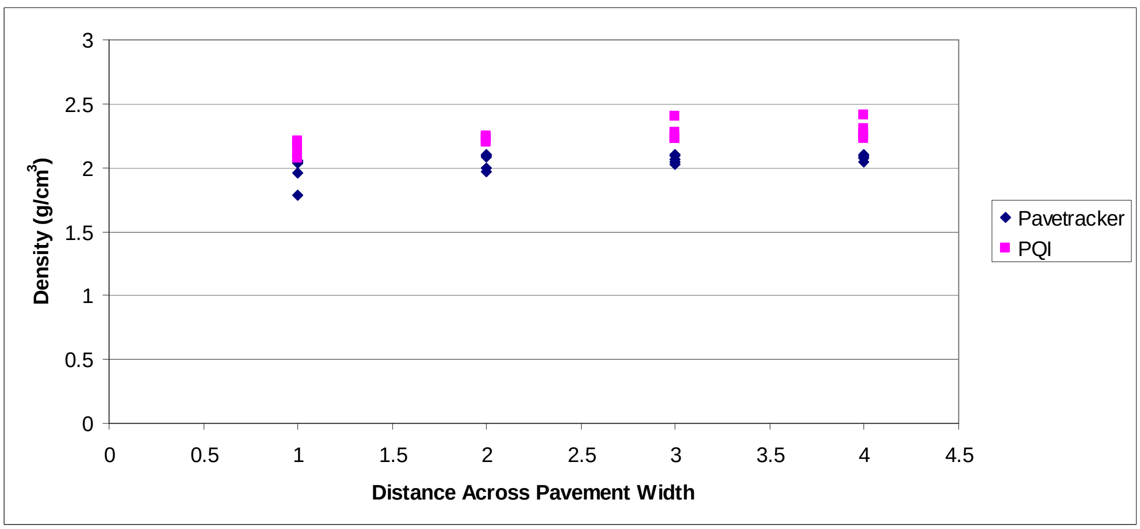

Figure 15. Site 2 final roller density readings

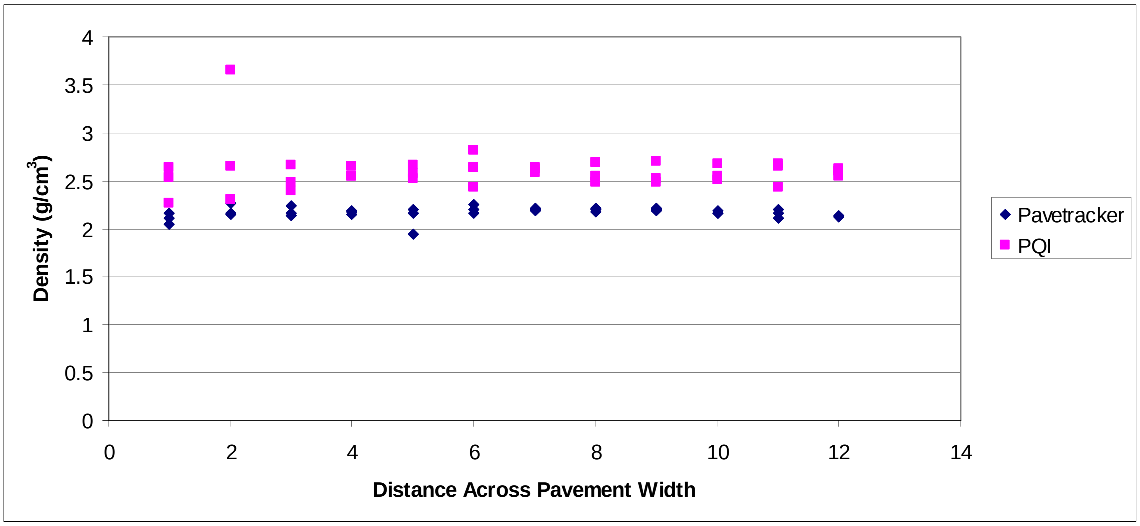

Figure 16. Site 3 final roller density readings

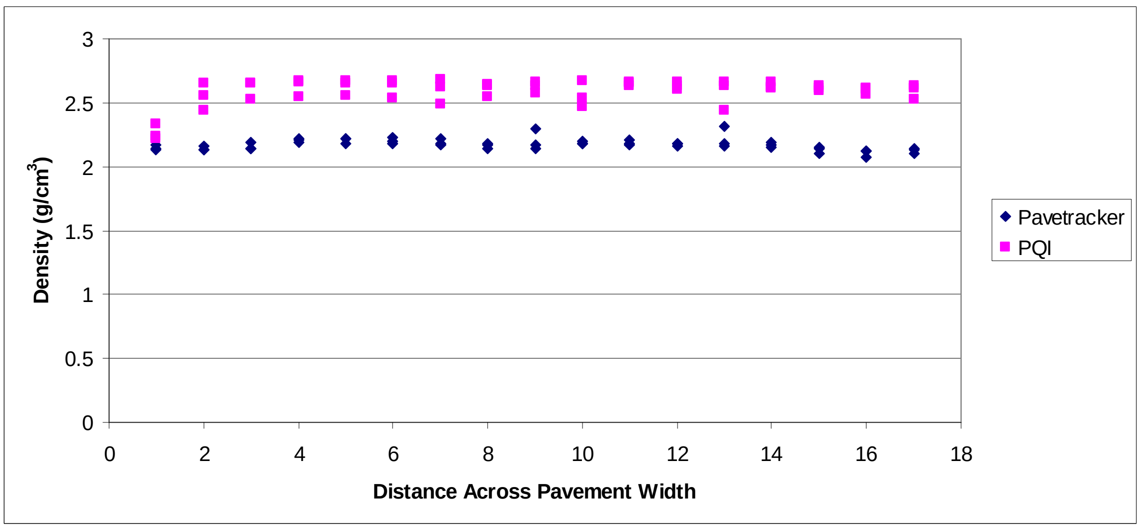

Figure 17. Site 4 final roller density readings

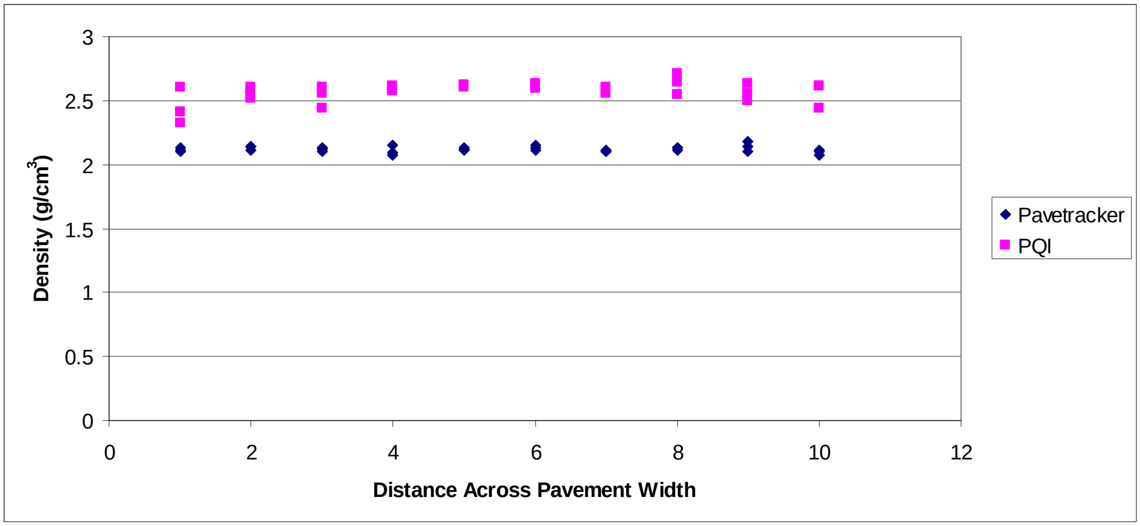

Figure 18. Site 5 final roller density readings

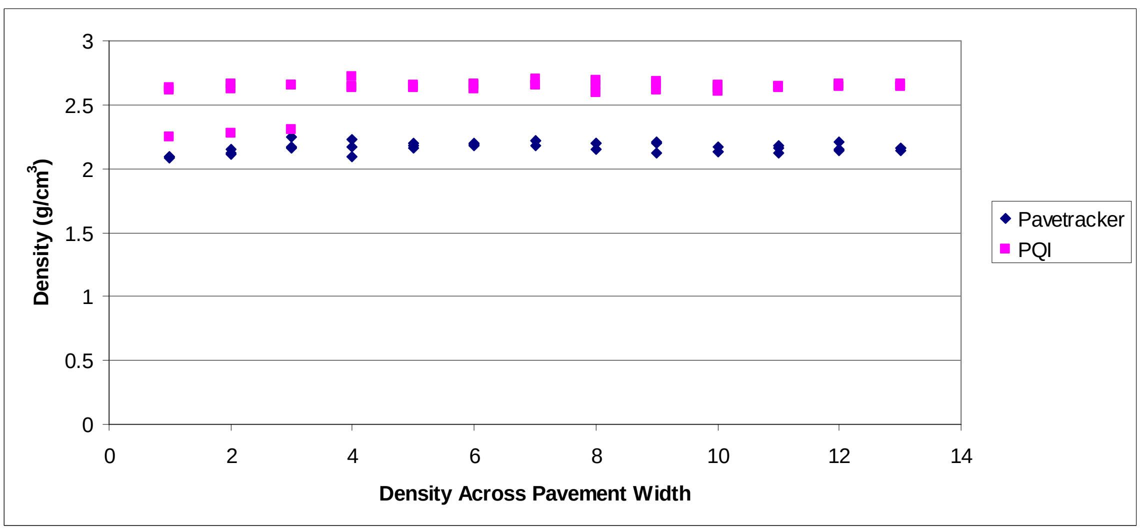

Figure 19. Site 6 final roller density readings

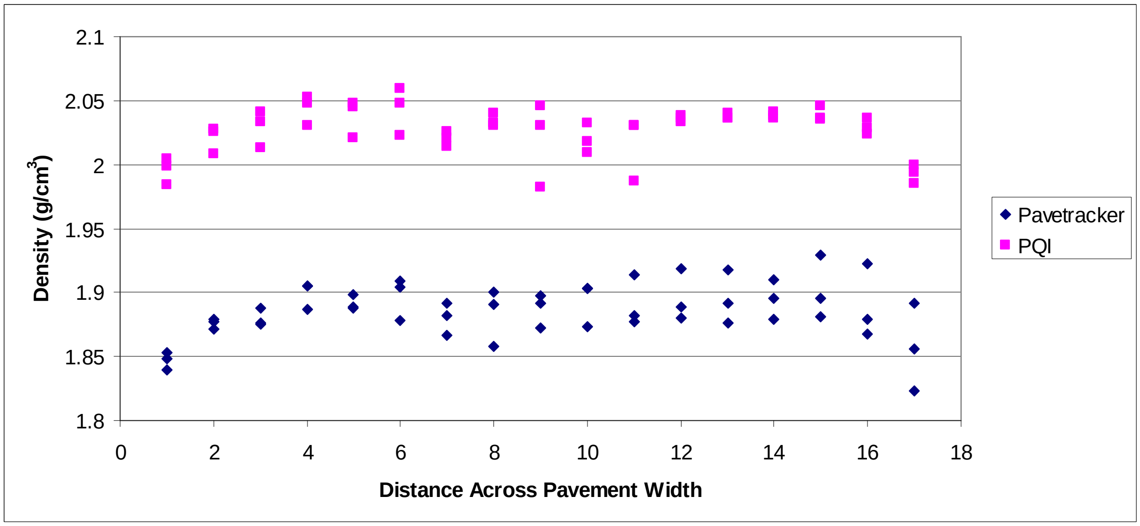

Figure 20. Site 7 final roller density readings

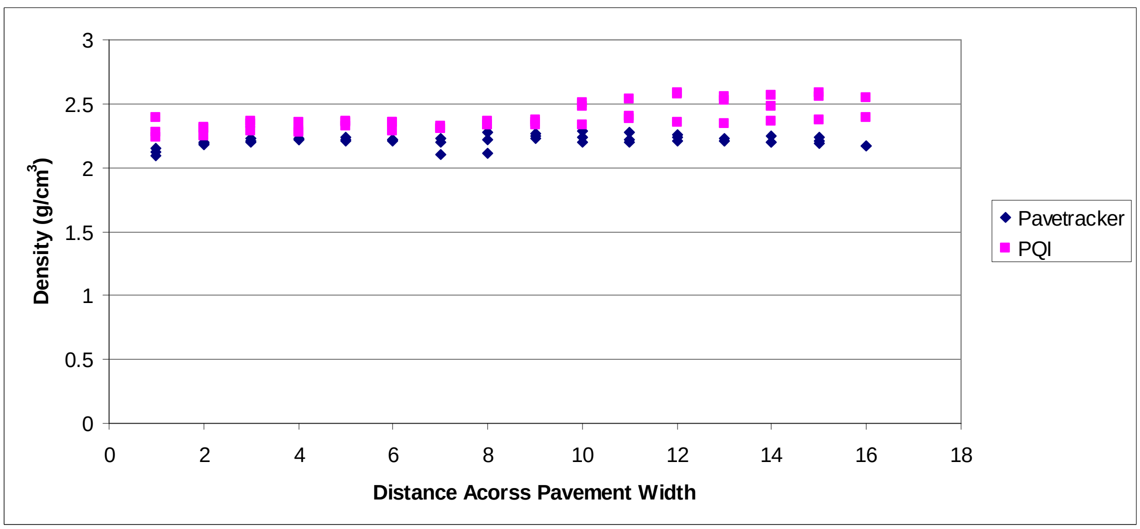

Figure 21. Site 8 final roller density readings

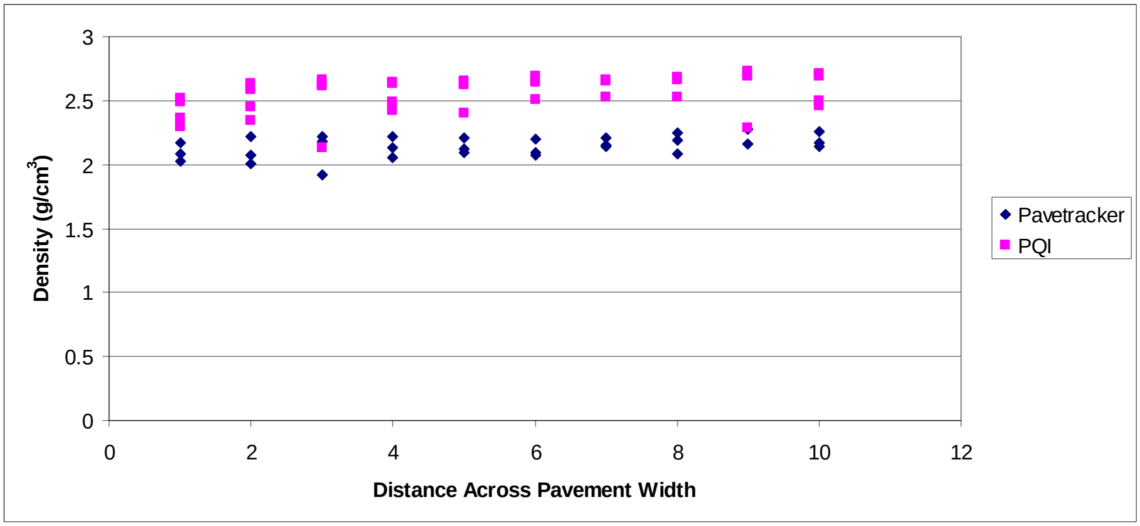

Figure 22. Site 9 final roller density readings

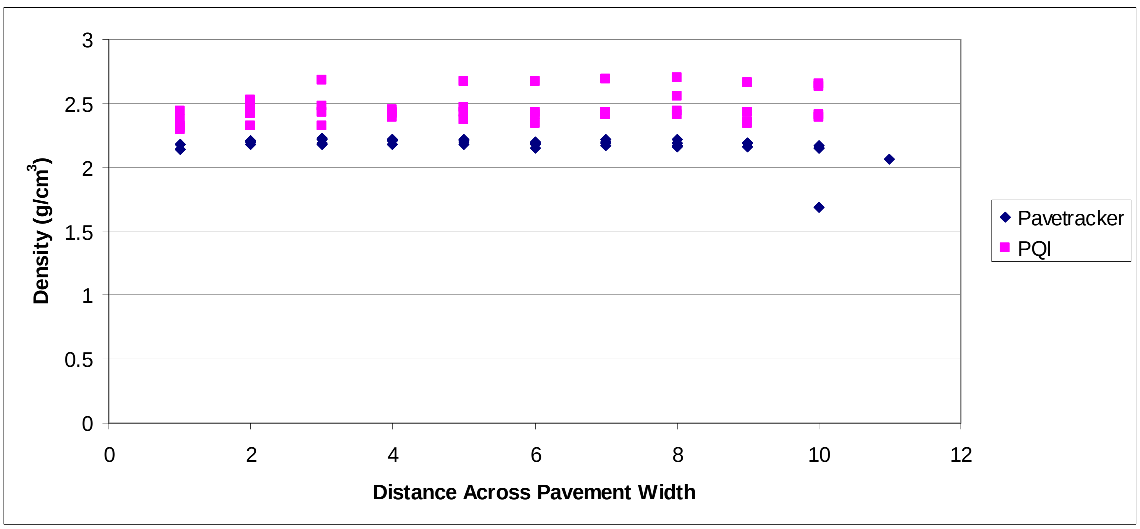

Figure 23. Site 10 final roller density readings

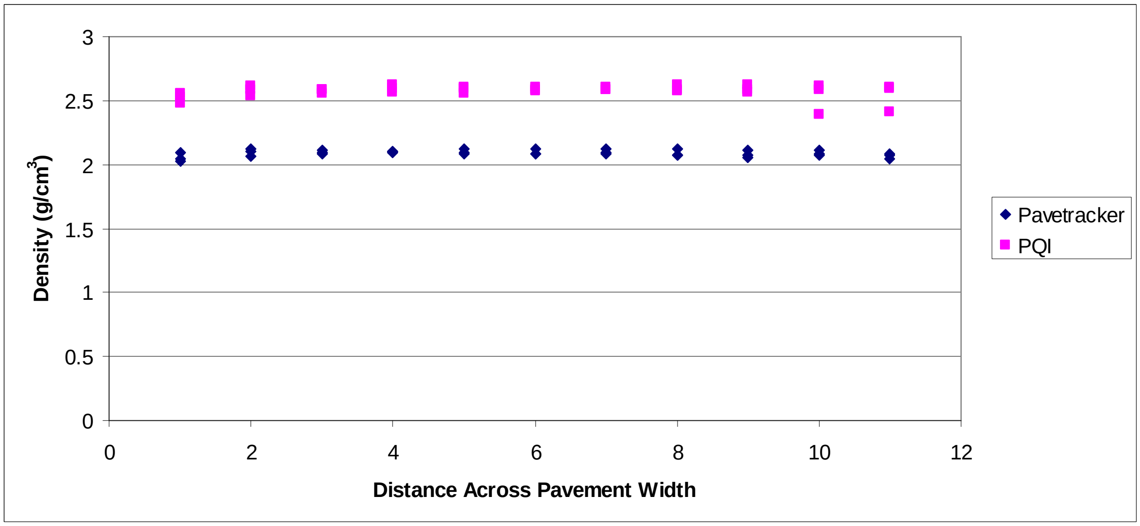

Figure 24. Site 11 final roller density readings

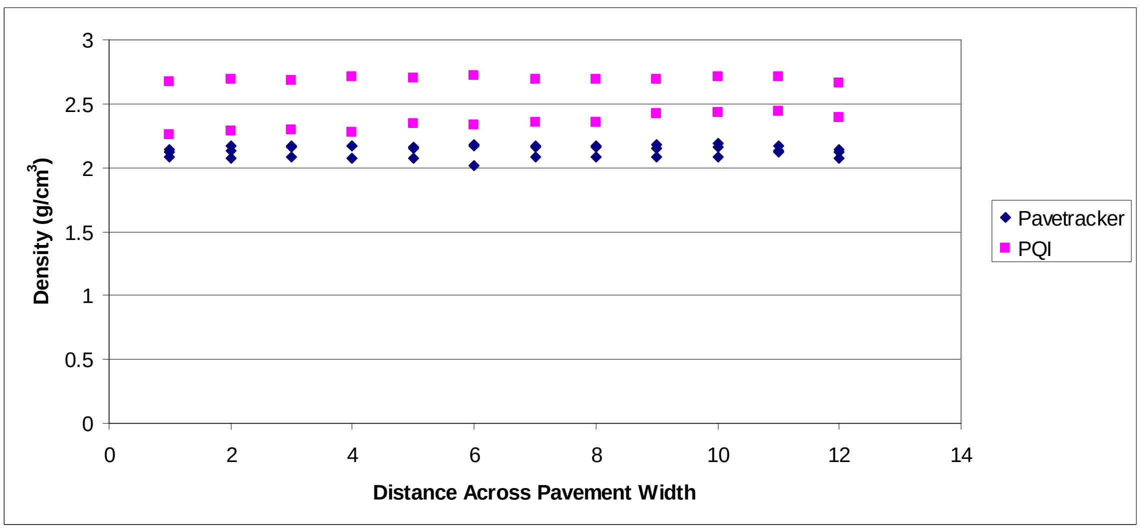

Figure 25. Site 12 final roller density readings

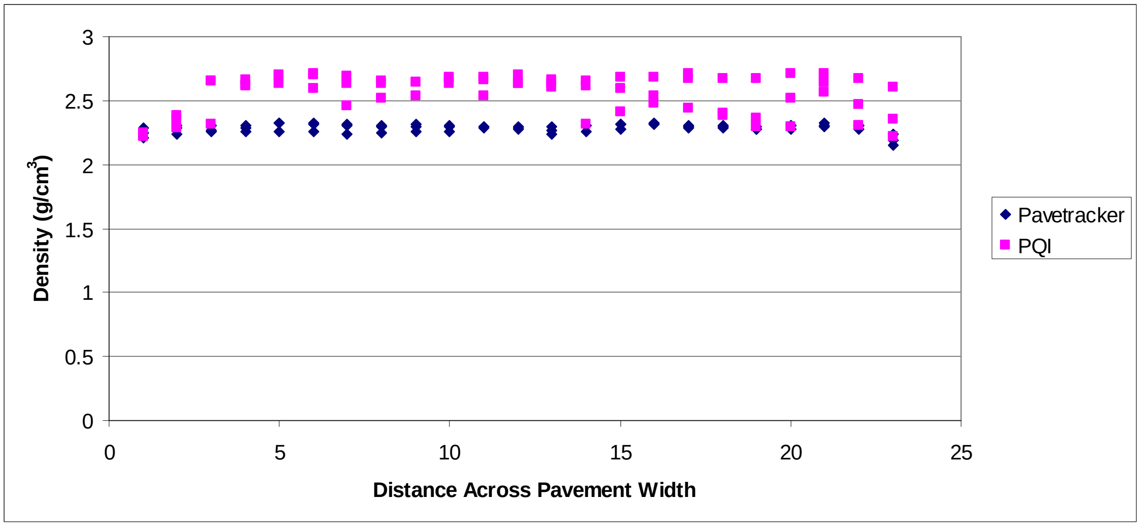

Figure 26. Site 13 final roller density readings

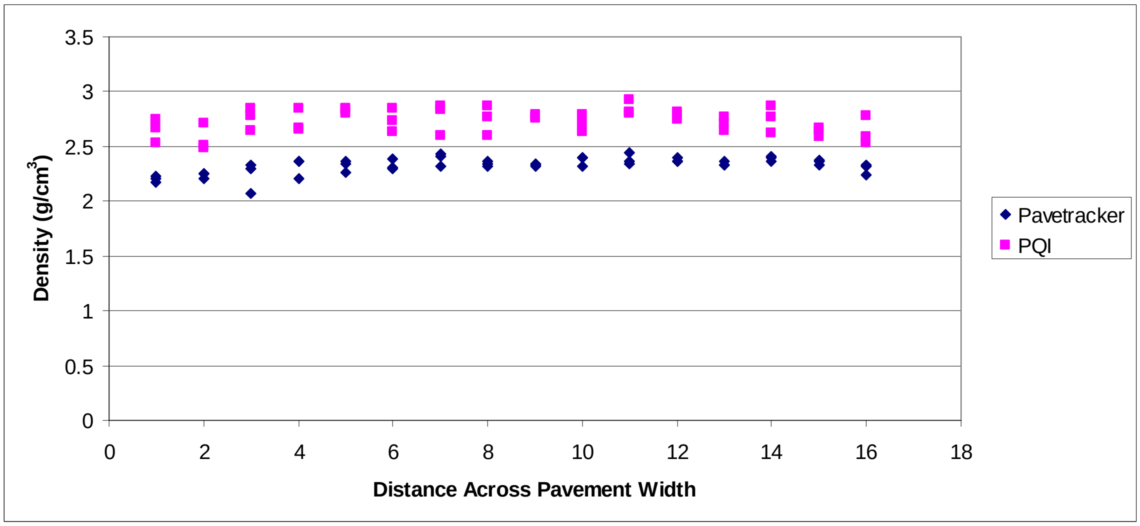

Figure 27. Site 14 final roller density readings

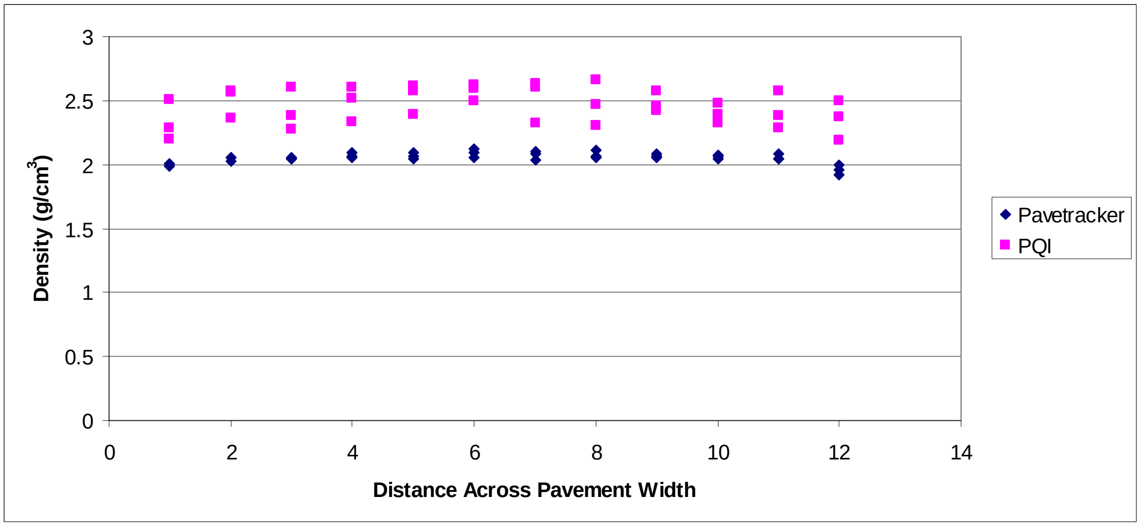

Figure 28. Site 15 final roller density readings

Additional graphs for gauge readings and core measurements are contained in the Appendix (Figures A1 through A17). These include mean, standard deviation, and coefficient of variation for core density and gauge density readings, as well as comparisons against quality indexes. No obvious trends in the graphs were found—other than the fact that the adjusted gauge readings relate directly to core density measurements, because the gauge readings were adjusted based on the core measurements and, thus, this correlation is expected.

6.3. Quality Assurance Density Conclusions

In this chapter, readings that could be used for quality assurance were evaluated. It was revealed that the location of a core across the width of a pavement can result in significantly different density readings for the same pavement. This variability should be accounted for when establishing the variability of a density determination method. The variability of a PQI tends to be greater than either a PaveTracker reading or an extracted core density.

Quality indices used for quality assurance were calculated for both unadjusted and adjusted data. The PQI quality indices for the unadjusted data were similar to the core quality indices for all but one site. However, when a correction factor was applied, seven out of fourteen sites differed from core quality indices. (No cores were pulled for site 4; therefore, a correction factor could not be calculated for site 4.) The PaveTracker quality indices for unadjusted data differed from the cores for eleven sites. However, when a correction factor was applied, the two agreed for all but one site.

7.0. ANALYSIS OF SLAB DENSITIES

Specimen slabs approximately two inches thick were procured in the laboratory from the loose mix obtained at testing sites. Five additional mixes were included in the laboratory testing to yield a total of 20 mixes. Two target air-void percentages were adopted when making the slabs, 4% and 7%. Four slabs per mix were made, two for each target air void. Density readings of each slab were obtained using both a PQI and PaveTracker, with the slabs either on a concrete floor or wood table. Readings were made on these two different surfaces to determine whether varying materials/density underneath the HMA being tested has an impact on the readings. All specimens tested were evaluated both wet and dry. Table 30 summarizes the testing plan executed for one mix. For each set, multiple readings were obtained for two slabs. This plan was repeated for all 20 mixes. PaveTracker readings were obtained by collecting four readings at the center of each slab. PQI readings followed the cloverleaf pattern, resulting in a set of five readings per slab. For example, site 1 had four slabs: two with 4% target air-void systems and two with 7% target air-void systems. Each of the four slabs was subjected to density readings using both the PQI and PaveTracker, in both wet and dry states, on both the concrete and wooden surfaces.

Table 30. Summary of testing for one mix

Target Air Voids	Condition	Testing Surface	Pavetracker	PQI
4	Dry	Concrete	2	2
		Wood Table	2	2
	Wet	Concrete	2	2
		Wood Table	2	2
7	Dry	Concrete	2	2
		Wood Table	2	2
	Wet	Concrete	2	2
		Wood Table	2	2

7.1. Analysis of Slab Densities

As with the field-collected densities, factors affecting laboratory density readings and mean comparisons were evaluated. Evaluations of class variables affecting density readings in the lab indicated that the significant factors are site, specimen condition (i.e., wet or dry), and the device used (i.e., PaveTracker or PQI). The results of the analysis are listed in Table 31. Evaluations of both class and continuous variables affecting density and nature of relationship are listed in Table 32. The regression analysis indicates that the variables affecting density readings are specimen condition (i.e., wet or dry), device used (i.e., PaveTracker or PQI), target air-void percentage, and aggregate type.

Table 31. Class variables affecting laboratory densities

Source	SS I	SS III
Site	•	•
Surface		
Condition	•	•
Aggregate Type		
Device	•	•
Air Voids		

Table 32. Regression analysis of factors affecting laboratory density readings

Variable	Parameter Estimate	Pr > |t|
Intercept	-0.84427	0.2109
Site	-2.67E-05	0.9873
Target Air Voids	0.01705	0.0271
Dry Weight	0.0000729	0.4227
Wet Weight	0.0002465	0.2536
SSD Weight	7.724E-05	0.6772
Condition	0.0794	<.0001
Testing Surface	-0.000614	0.973
Aggregate Type	-0.03123	0.0288
Device	0.20425	<.0001

After determining which factors appear to statistically affect density readings obtained from laboratory-procured slabs, mean comparisons of factor levels were conducted. Interestingly, density mean comparisons by aggregate type did not yield any significantly different groupings. In other words, slabs with slag did not yield significantly different values than slabs without slag. Table 33 summarizes the results of mean comparisons, grouping densities by site. The Tukey Groupings indicate whether or not different sites can be considered from the same group. For example, both site 1 and 2 have a C; therefore, these two sites can be considered to have densities from the same distribution. Table 34 summarizes the results of mean comparison testing, grouping densities by specimen condition (i.e., wet or dry). The evaluation suggests that wet specimen densities differ significantly from dry specimen densities. Table 35 summarizes the mean comparison between PaveTracker and PQI density readings. The results imply that the readings are significantly different. Mean comparisons of densities obtained from a PQI, PaveTracker, and the traditional method (i.e., saturated, surface dry bulk specific gravity of a slab) indicate that none of the groups could be considered from the same distribution. However, the average differences were small.

Table 33. Summary of density mean comparisons by site

Site	Number of Readings	Mean	Tukey Grouping
1	144	2.36657	B D A C
2	144	2.24038	D C
3	144	2.42073	B A C
4	144	2.27979	B D A C
5	144	2.3075	B D A C
6	144	2.30339	B D A C
7	144	2.01744	E
8	144	2.36082	B D A C
9	144	2.27056	B D C
10	144	2.26698	B D C
11	144	2.21717	D E
12	144	2.36747	B D A C
13	144	2.3643	B D A C
14	144	2.47412	A
15	144	2.24776	D C
16	144	2.27699	B D A C
17	144	2.32338	B D A C
18	144	2.46145	B A
19	144	2.30658	B D A C
20	144	2.28426	B D A C

Table 34. Summary of density mean comparisons by condition

Condition	Number of Readings	Mean	Tukey Grouping
Wet	1440	2.34758	A
Dry	1440	2.26818	B

Table 35. Summary of density mean comparisons by electromagnetic device

Device	Number of Readings	Mean	Tukey Grouping
PQI	1600	2.39866	A
Pavetracker	1280	2.19441	B

7.2. Analysis of PQI Center Data

The base of the PQI was diametrically larger than the slab widths. An analysis was conducted to determine if different density readings were yielded when part of a PQI base went beyond a slab edge, versus a reading where the base was completely in contact with a slab. The analysis indicated that for all sites with the exception of three, there is no statistical difference in the readings. The three sites that did yield statistically different results were sites 2, 14, and 19. Sites 2, 14, and 19 all contain slag, whereas none of the other sites' mixes contained slag.

7.3. Analysis of the New PQI Algorithm

A new algorithm was developed for PQIs in order to more accurately determine densities. After evaluating densities of laboratory-procured slabs with a PQI using the old algorithm, the same slabs were evaluated using the latest algorithm. This section outlines an analysis of the new algorithm, including a comparison with the old algorithm which was used for the majority of the project and, in particular, for all field measurements.

Mean comparisons were conducted to determine significant differences between factor levels. Table 36 summarizes the results of mean comparisons of densities by mix. Mixes with at least one letter in common cannot be considered statistically different.

Table 36. Mean comparisons of densities by mix using new PQI algorithm

Mix	Mean Density	Tukey Grouping		
1	2.093	E	D	F
2	1.994			F
3	2.062	E	D	F
4	2.073	E	D	F
5	2.085	E	D	F
6	2.160	B	D	C
7	2.249	B	A	
8	2.219	B	A	C
9	2.049	E		F
10	2.245	B	A	
11	2.076	E	D	F
12	2.124	E	D	C
13	2.099	E	D	
14	2.293		A	
15	1.999			F
16	2.288		A	
17	2.235	B	A	
18	2.040	E		F
19	2.034	E		F
20	2.210	B	A	C

Other mean comparison groupings evaluated indicated that the respective groups could not be deemed statistically different. Grouping by condition or test surface did not yield any statistical differences. However, grouping by aggregate type resulted in all levels being deemed statistically different from one another. In other words, a mix with quartzite yields statistically different results than a limestone and/or slag mix.

Densities obtained using the new PQI algorithm were compared with the other densities collected. The analysis indicated that the new PQI algorithm differs from the old PQI algorithm, PaveTracker, and core densities. Interestingly, the mean densities obtained via the new algorithm were closest to the PaveTracker readings. However, the variability was similar to the old PQI algorithm. Overall, it seems that the new PQI algorithm yields more accurate results without losing much precision, as compared with the old algorithm.

7.4. Laboratory Density Conclusions

In the laboratory, both wet and dry specimens were evaluated on two different surfaces. For the laboratory tests, slabs were procured in such a way as to reduce the amount of variability. The analysis indicates that when the same compacting device is used to procure specimens, only specimen condition (i.e., wet or dry) and density reading device (i.e., PQI or PaveTracker) affects density results. This implies that mixes with slag can be evaluated with either device and not yield significantly different results than, for instance, a limestone mix compacted to the same percent air voids.

Evaluations of single-center PQI readings and multiple PQI slab readings were conducted. The analysis indicated that, for all mixes except ones containing slag, results obtained when the footprint of a PQI exceeds the area of a specimen are equivalent to those obtained when a PQI does *not* exceed a specimen area. This is the only instance when mixes with slag differed from other mixes when evaluating laboratory slab data. The new algorithm for a PQI was also evaluated. It was found that the new algorithm is more accurate than the old one with about the same level of precision. It is recommended that the new algorithm be employed when conducting future research with a PQI.

8.0. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to evaluate the use of electromagnetic gauges to nondestructively determine densities. Two electromagnetic gauges were used, a PaveTracker and a PQI, for making field and laboratory measurements. Test data was collected in the field during and after paving operations and also in a laboratory on field mixes compacted in the lab.

Analyses of both devices indicate that both are sensitive to density changes due to roller passes (See Appendix). Sensitivity to density changes after roller passes is viewed as favorable since it indicates that these devices could be used for quality control. Statistical evaluations indicate that the majority of density readings obtained via electromagnetic gauges and cores differed. However, these differences do not relate whether the readings would affect overall quality assurance conclusions. To evaluate whether quality assurance conclusions would be altered by using an electromagnetic gauge, quality indices were calculated. The quality indices of the unadjusted data revealed that, even though the PQI readings tended to be much greater than the other two methods, quality assurance conclusions in most cases would be equivalent to ones obtained based on cores. The PaveTracker densities, if used for determination of payment, would have resulted in several contractors receiving a penalty.

8.1. PaveTracker Conclusions

The PaveTracker device was used in the field at both random and core locations. Analysis was conducted to determine which factors significantly affect PaveTracker readings in the field. Roller pass was deemed statistically significant, which indicates that a PaveTracker is sensitive to changes in density caused by roller passes. The regression analysis implied that condition (i.e., wet or dry), contractor, aggregate type, NMAS, traffic level, and roller pass were all significant variables affecting PaveTracker density readings. The two sites that differed the most from the other sites where PaveTracker data was collected were sites 7 and 15. Mean comparisons revealed that there are significant differences between wet density readings and dry density readings as well as between traffic levels and roller passes. Mixes with slag also appear to be statistically different than those without slag. 19.0-mm and 12.5-mm NMAS mixes were not found to be statistically different. Correlation analysis revealed that there are slightly strong relationships for traffic level–aggregate type, and traffic level–binder content. The analysis indicates that a PaveTracker is sensitive to density changes, and further research should be conducted to evaluate areas of difference and to establish guidelines for use in Iowa.

8.2. PQI Conclusions

Two methods for collecting PQI density readings were employed: single mode and multi mode. For the single mode, evaluations of class variables indicated that station, roller pass, and distance across pavement width significantly affected PQI results. The regression analysis of the single-mode data revealed that station, pavement width, distance across pavement width, and temperature are significant. The four sites found to have significantly different results than the other sites, according to the single-mode data, were sites 2, 7, 8, and 15. The majority of contractor comparisons were deemed statistically significant when evaluating the single-mode data. Slag was also found to significantly affect the readings.

Multi-mode data evaluations also found the following class variables to be significant: station, roller pass, and distance across pavement width. Regression analysis of multi-mode data revealed that site, station, pavement width, contractor, aggregate type, binder content, roller pass, and distance across pavement width were significant variables. Mean comparisons revealed that four sites differed significantly when comparing multi-mode data: sites 2, 7, 12, and 15. Like the single-mode PQI data, comparisons of contractors resulted in almost all pairings being deemed significant. However, unlike the single-mode PQI data, the multi-mode data evaluations did not find aggregate type to be significant.

8.3. Comparison of PQI and PaveTracker

Table 37 and Table 38 summarize the variables affecting electromagnetic gauge readings. From Table 37, it can be seen that station and roller pass are significant for all three electromagnetic gauge readings. Both PQI data sets also found transverse pavement location significant. According to the regression analysis, there are no variables considered statistically significant for all three electromagnetic gauge datasets. However, there are several variables which two of the three data sets deemed statistically significant; both PaveTracker and multi-mode PQI readings are significantly affected by contractor, aggregate type, binder content, and roller pass.

Table 37. Summary of class variables affecting electromagnetic gauges

	PaveTracker		PQI Single Mode		PQI Multi Mode	
Source	**SSI**	**SSIII**	**SSI**	**SSIII**	**SSI**	**SSIII**
Site	•		•		•	
Station		•	•	•	•	•
Pavement Width		•				
Pavement Condition			N/A	N/A	•	
Contractor						
Aggregate Type						
NMAS						
Traffic Level						
Roller	•	•	•	•	•	•
Distance Across Pavement Width			•	•	•	•

Table 38. Summary of regression analysis for electromagnetic gauges

	PaveTracker		PQI Single Mode		PQI Multi Mode	
Variable	Paramter Estimate	Pr > |t|	Parameter Estimate	Pr > |t|	Parameter Estimate	Pr > |t|
Intercept	155.8388	<.0001	125.21586	0.0049	152.79259	<.0001
Site	-0.10602	0.4913	-0.67661	0.0676	1.72543	<.0001
Station	1.10806	0.0369	2.68108	0.1471	-0.54766	0.3012
Width	0.03274	0.8469	-1.02782	0.661	-0.50271	0.0082
Condition	-13.084	0.0237	N/A	N/A	2.22136	0.233
Contractor	-1.56077	<.0001	5.9159	0.2058	-2.67693	<.0001
Aggregate Type	-6.38087	<.0001	-0.81495	0.0595	10.33595	<.0001
Binder Content	7.38617	0.0017	3.73E-07	0.0909	-3.98782	0.0287
NMAS	-1.68917	<.0001	1.57909	0.0024	0.57366	0.2228
Traffic Level	-1.56E-07	0.2021	0.98876	0.0431	1.45E-07	0.0541
Roller Pass	-4.53788	<.0001	-0.86985	0.4475	-4.88213	<.0001
Distance Across Pavement	0.07371	0.4830	0.2423	0.0166	-0.89696	<.0001
Temperature	N/A	N/A	-0.06728	0.0016	N/A	N/A

8.4. Quality Assurance Density Conclusions

In this chapter, readings that could be used for quality assurance were evaluated. It was revealed that the location of a core across the width of a pavement (i.e., transverse location) can result in significantly different density readings for the same pavement. The variability of a PQI tends to be greater than either the PaveTracker or extracted core density variability.

Quality indices used for quality assurance were calculated for both unadjusted and adjusted data. The PQI quality indices for the unadjusted data were similar to the core quality indices for all but one site. However, when a correction factor was applied, seven out of fourteen sites differed from core quality indices. (No cores were pulled for site 4; therefore, a correction factor could not be calculated for site 4.) The PaveTracker quality indices for unadjusted data differed from the cores for eleven sites. However, when a correction factor was applied, the two agreed for all but one site.

8.5. Laboratory Density Conclusions

In the laboratory, both wet and dry specimens were evaluated on two different surfaces. For the laboratory tests, slabs were procured in such a way as to reduce the amount of variability. The analysis indicates that when the same compacting device is used to procure specimens, only specimen condition (i.e., wet or dry) and density reading device (PQI and PaveTracker) affect density results. This implies that mixes with slag can be evaluated with either device and not yield significantly different results than, for instance, a limestone mix compacted to the same percent air voids.

Evaluations of single center PQI readings and all PQI slab readings were conducted. The analysis indicated that, for all mixes except ones containing slag, results obtained when the footprint of a PQI exceeds the area of a specimen the results are equivalent to those obtained when a PQI does not exceed a specimen area. This is the only instance when mixes with slag differed from other mixes when evaluating laboratory slab data. The new algorithm for a PQI was also evaluated. It was found that the new algorithm is more accurate than the old with about the same level of precision. It is recommended that the new algorithm be employed when conducting future research with a PQI.

8.6. Recommendations

This detailed study has found several mix- and project-specific factors that affect electromagnetic gauge readings. Thus, the implementation of these gauges will likely need to be done utilizing a test strip on a project- and mix-specific basis to appropriately identify an adjustment factor for the specific electromagnetic gauge being used for quality control and quality assurance testing (QC/QA). The substantial reduction in testing time that results from employing electromagnetic gauges rather than coring makes it possible for more readings to be used in the QC/QA process with real-time information without increasing the testing costs. To ensure the appropriate implementation of electromagnetic gauges, there is a need for additional work that considers the following elements:

1. the utilization of test strips,

2. increased electromagnetic gauge testing frequency, and

3. new electromagnetic gauges that have entered the construction industry (e.g., PQI models 302 and 303). The PQI model 302 gauge has been available since 2005, and the 303 model's release is anticipated as soon as 2007.

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APPENDIX: GRAPHICAL REPRESENTATIONS OF GAUGE READINGS AND CORE MEASUREMENTS

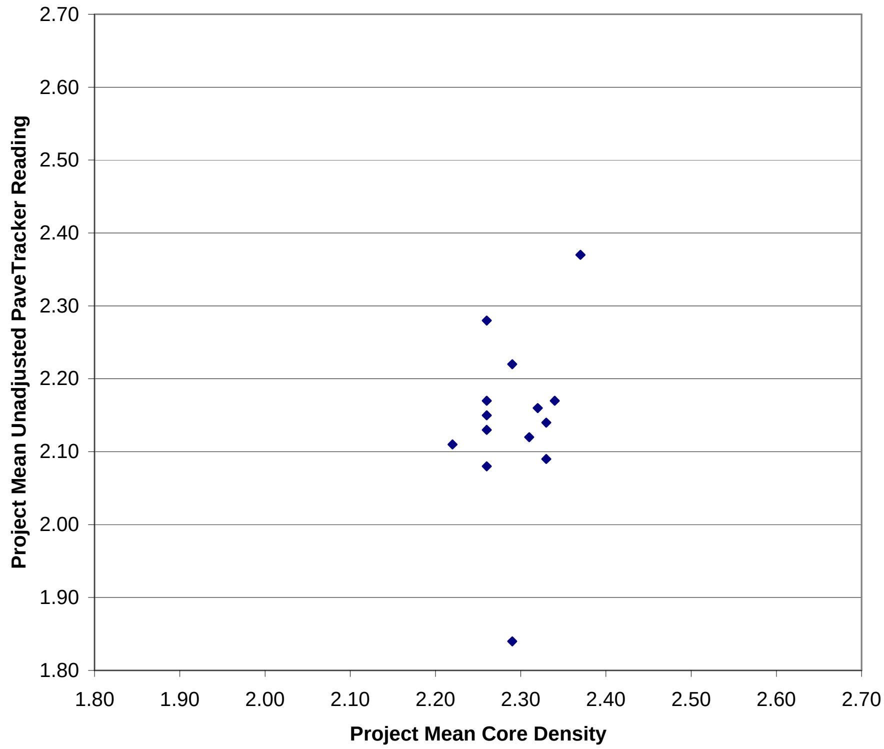

Figure A.1. Core density (g/cm^3) versus unadjusted PaveTracker readings

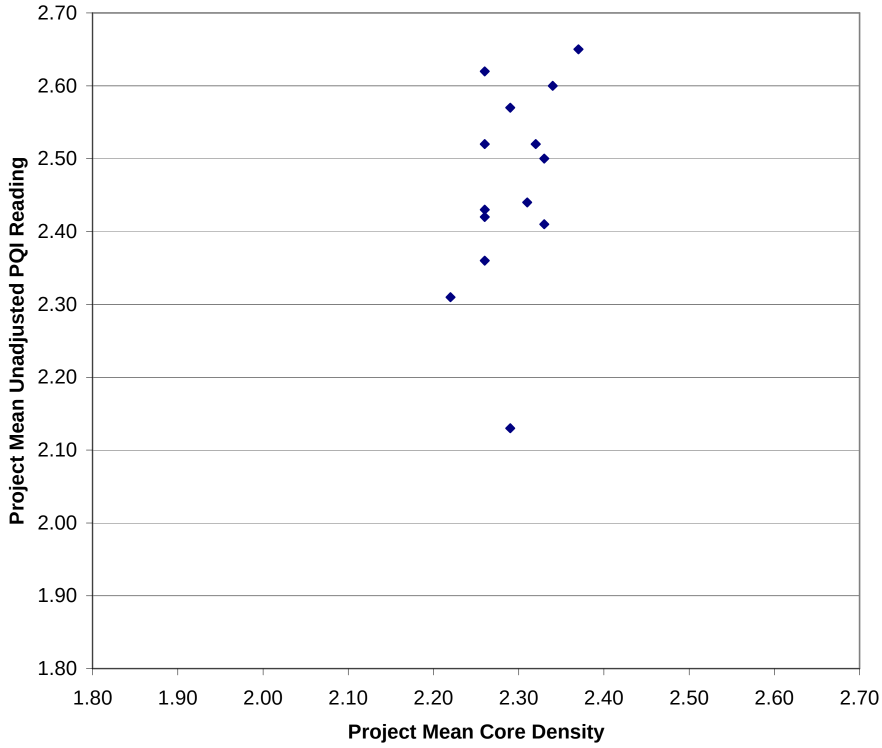

Figure A.2. Core density (g/cm^3) versus unadjusted PQI readings

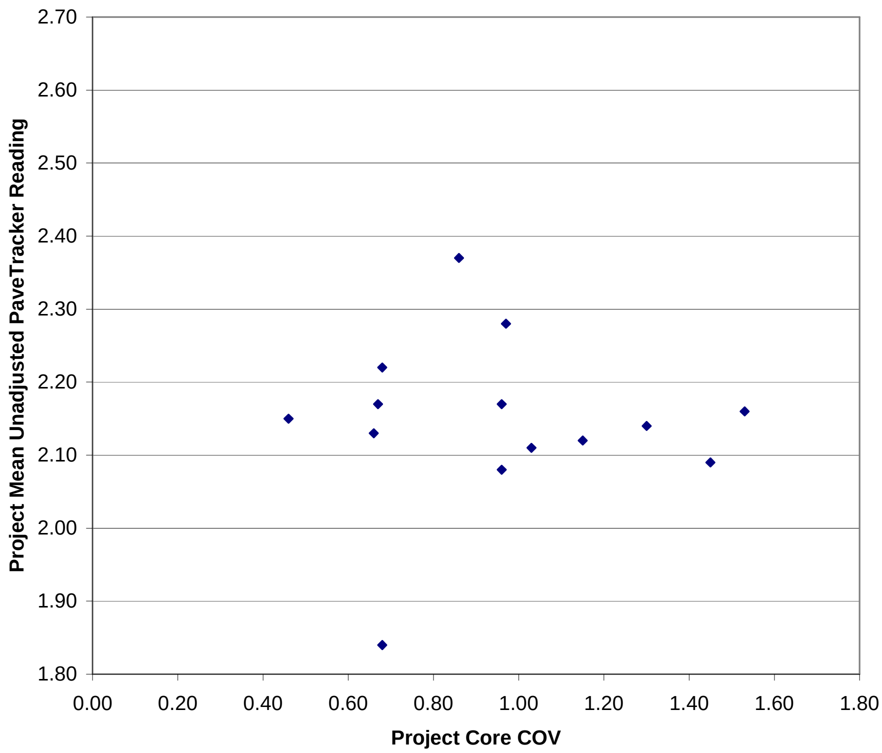

Figure A.3. Core coefficient of variation (g/cm^3) versus unadjusted PaveTracker readings

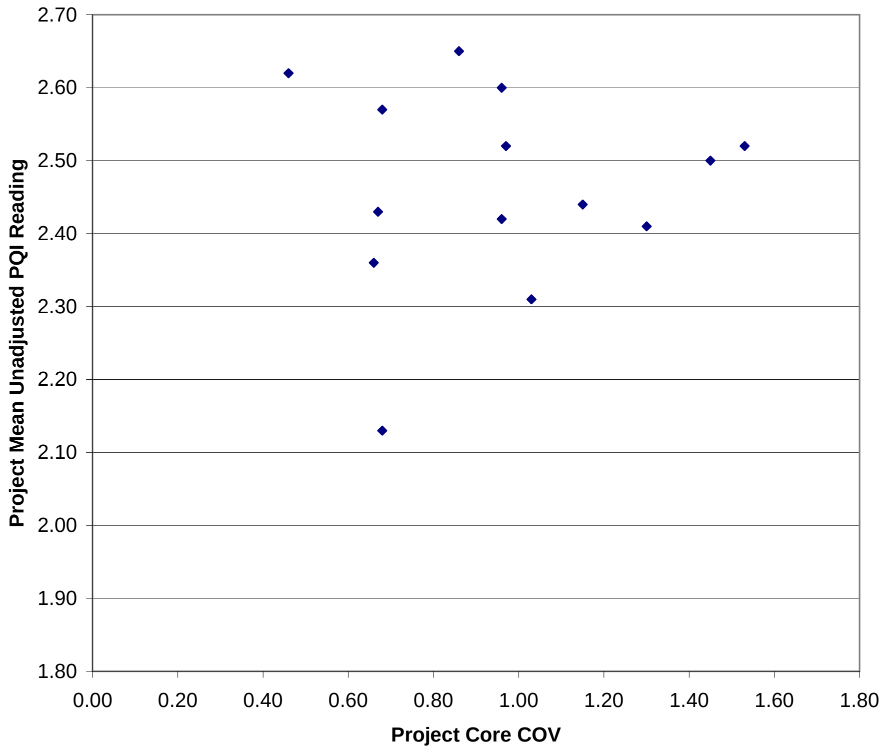

Figure A.4. Core coefficient of variation (g/cm^3) versus unadjusted PQI readings

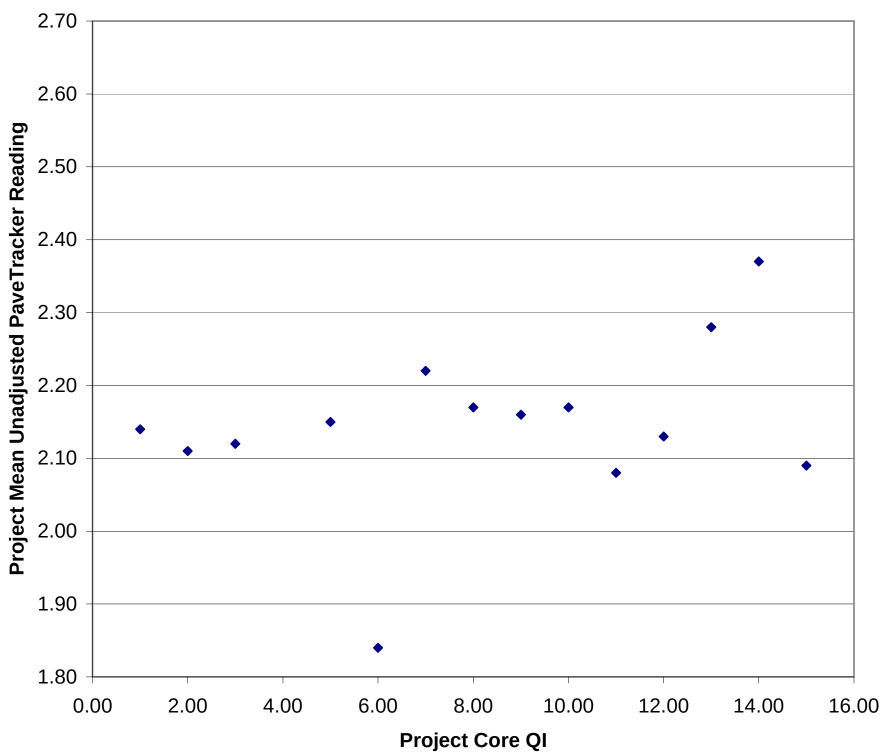

Figure A.5. Core quality index versus unadjusted PaveTracker readings

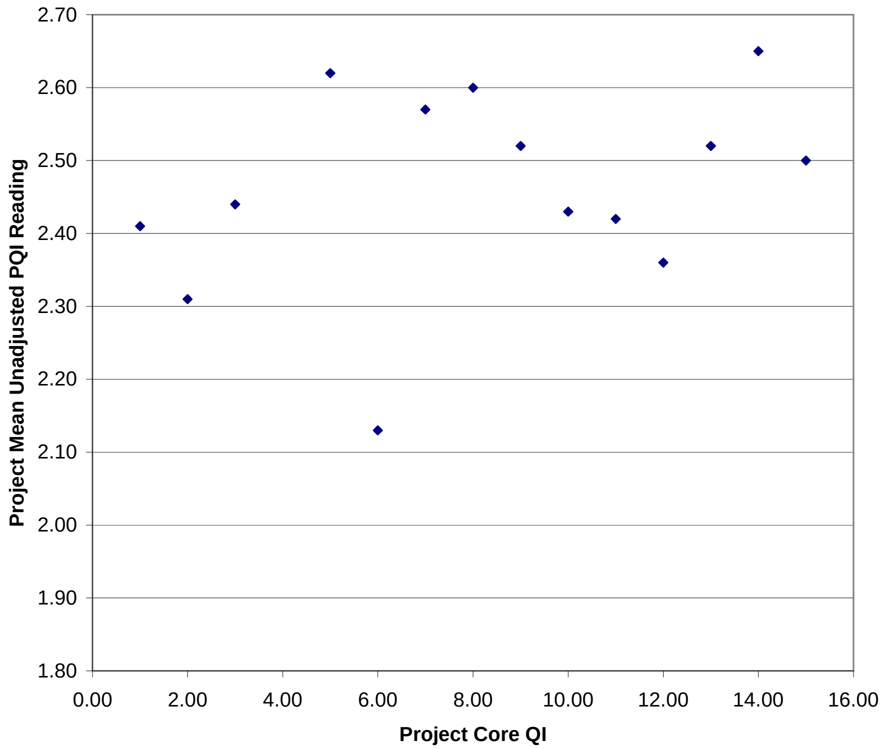

Figure A.6. Core quality index versus unadjusted PQI readings

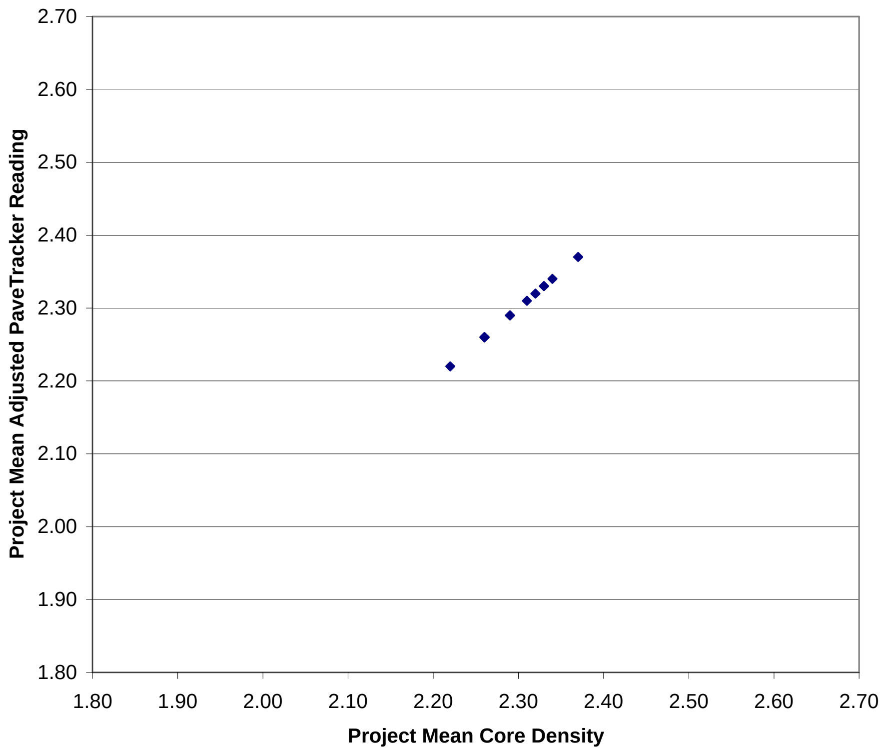

Figure A.7. Core density (g/cm^3) versus adjusted PaveTracker readings

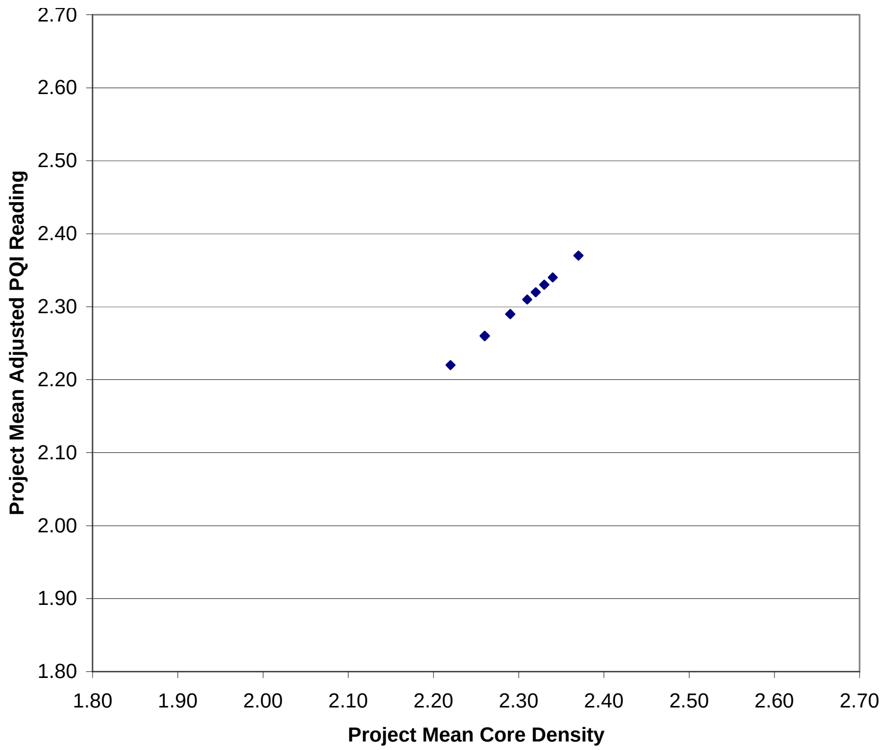

Figure A.8. Core density (g/cm^3) versus adjusted PQI readings

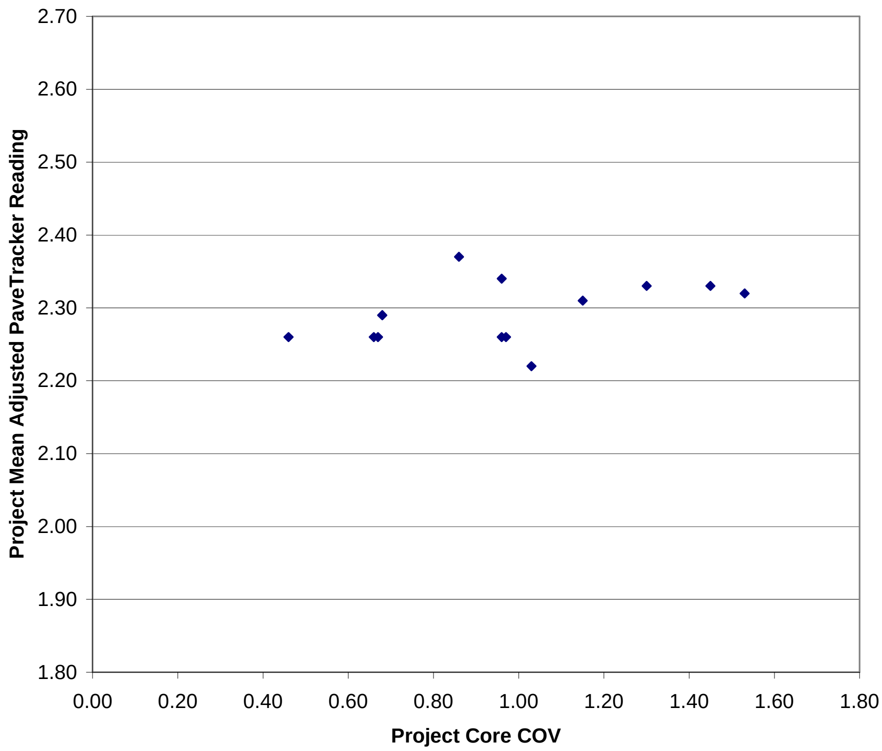

Figure A.9. Core coefficient of variation (g/cm^3) versus adjusted PaveTracker readings

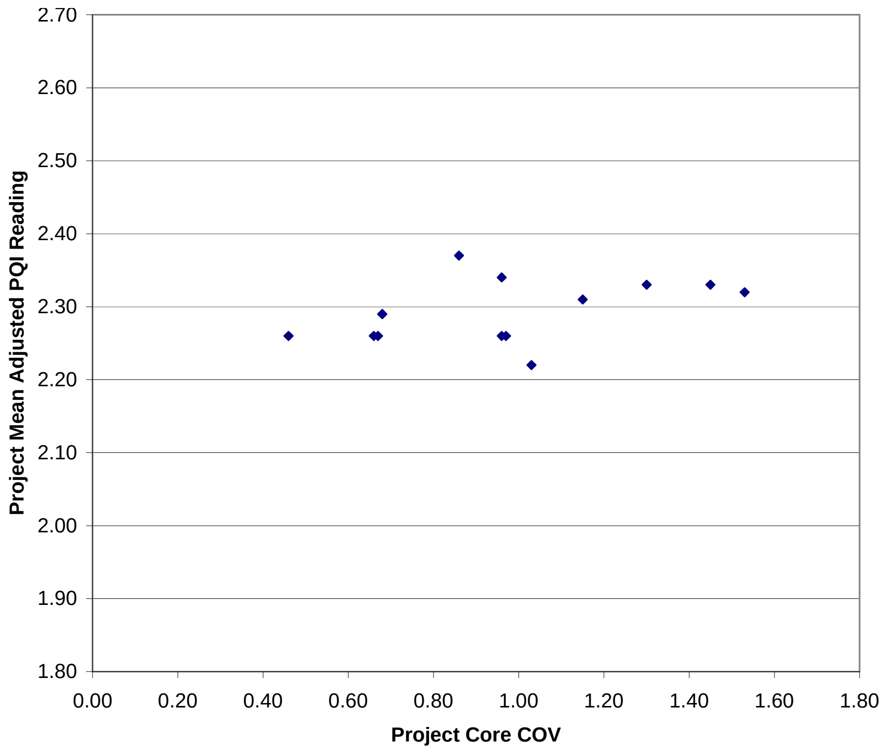

Figure A.10. Core coefficient of variation (g/cm^3) versus adjusted PQI readings

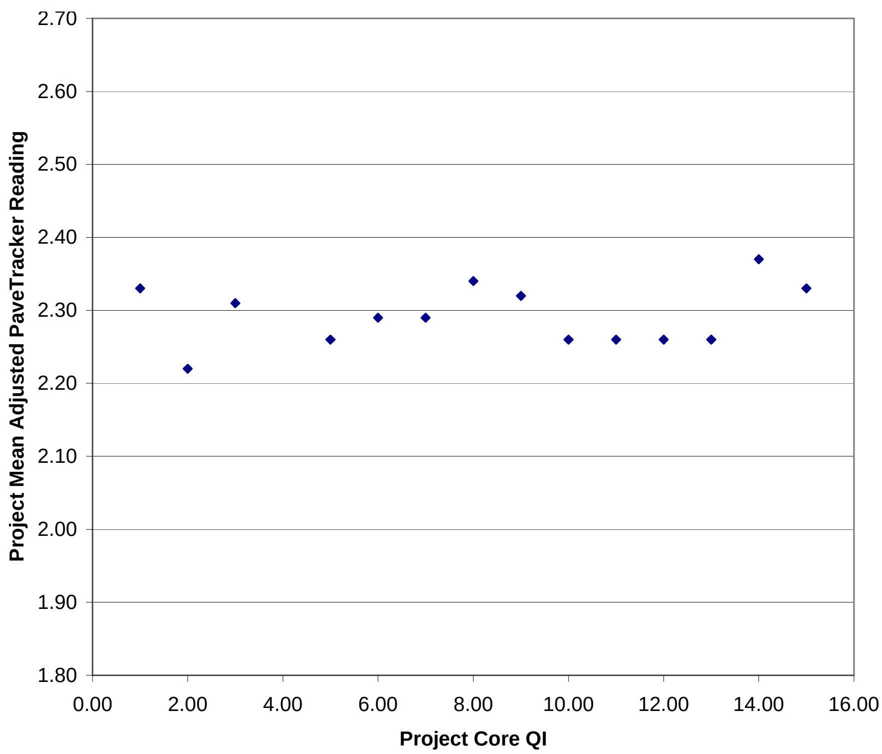

Figure A.11. Core quality index versus adjusted PaveTracker readings

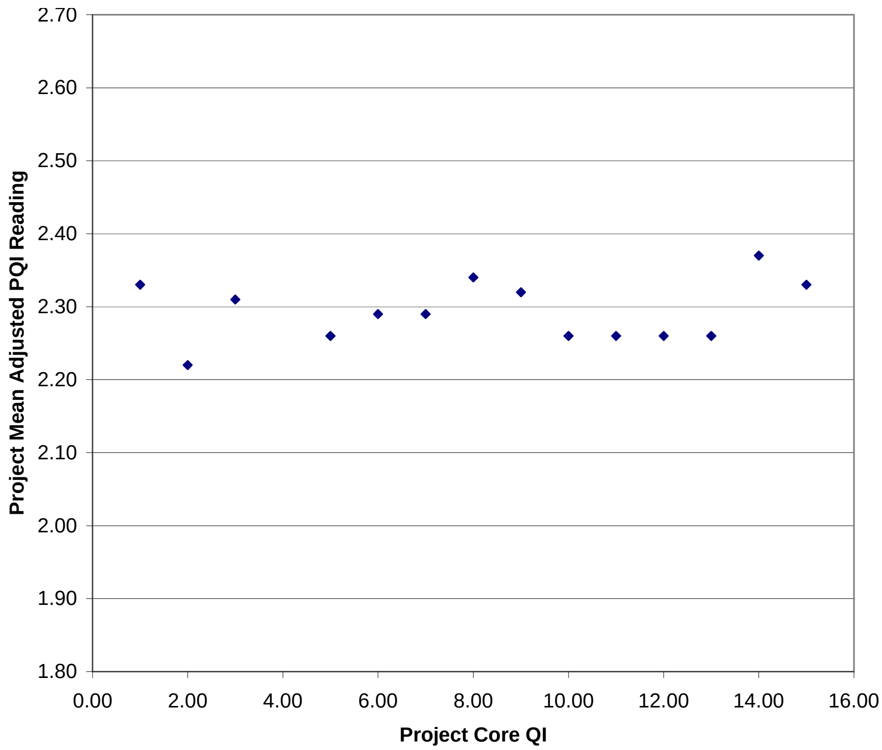

Figure A.12. Core quality index versus adjusted PQI readings

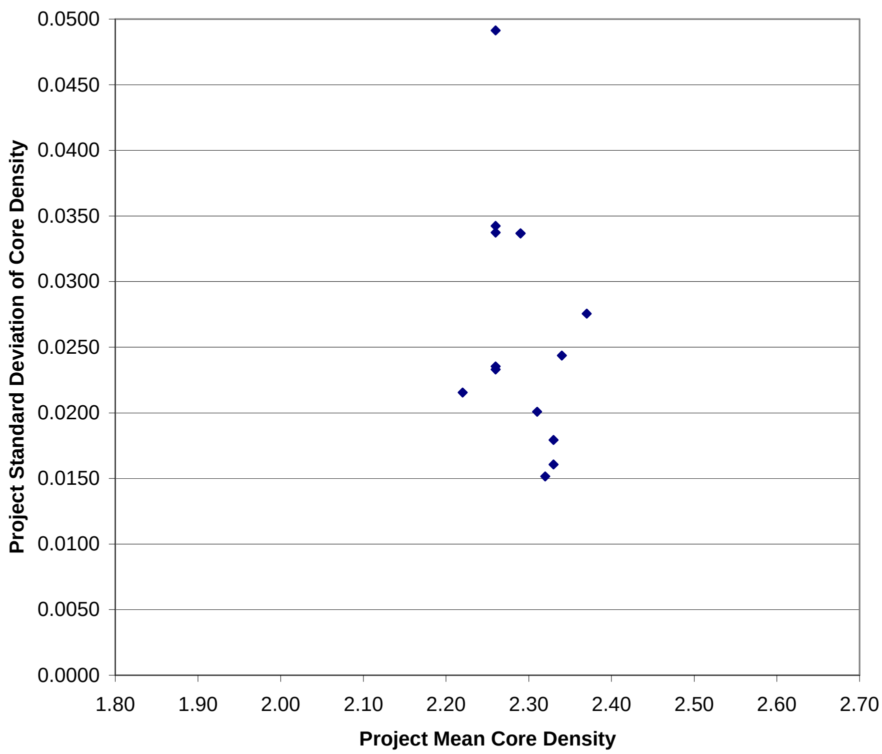

Figure A.13. Core mean density (g/cm^3) versus standard deviation of core density (g/cm^3)

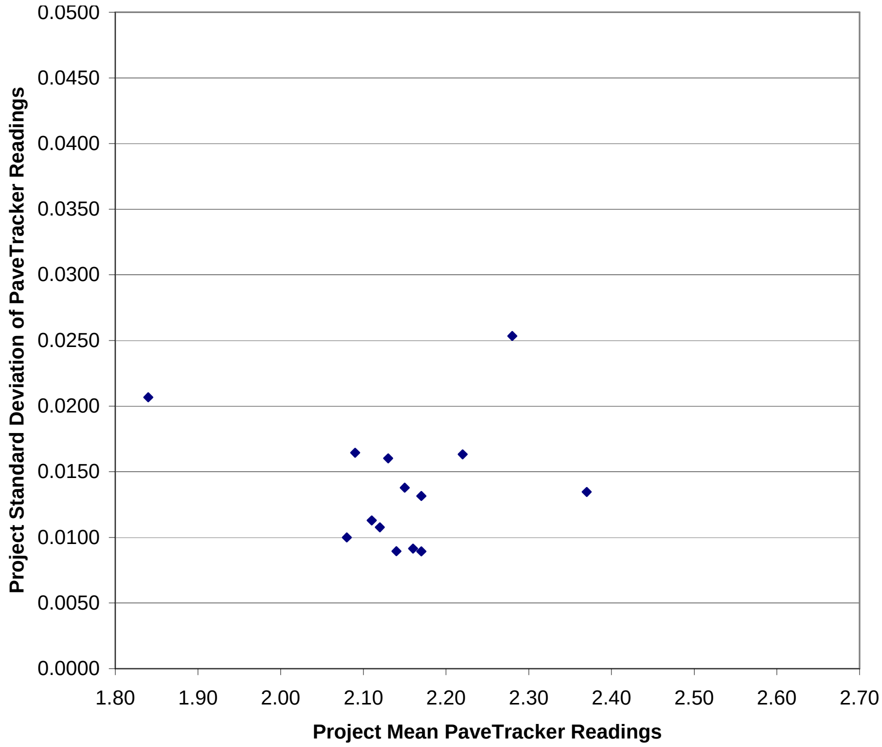

Figure A.14. PaveTracker unadjusted mean readings versus standard deviation of PaveTracker readings

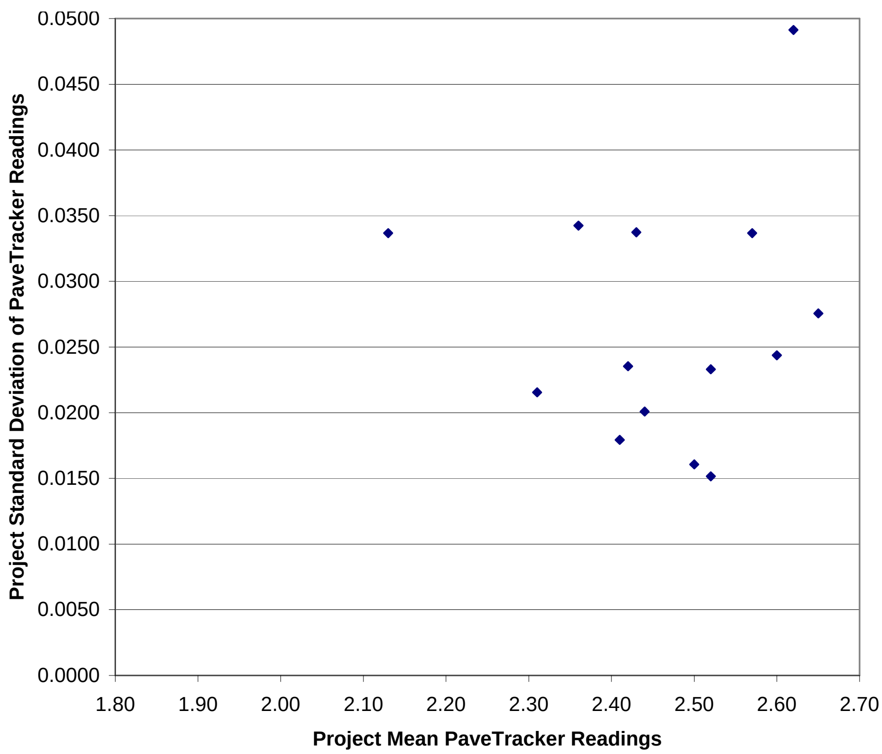

Figure A.15. PQI unadjusted mean readings versus standard deviation of PQI readings

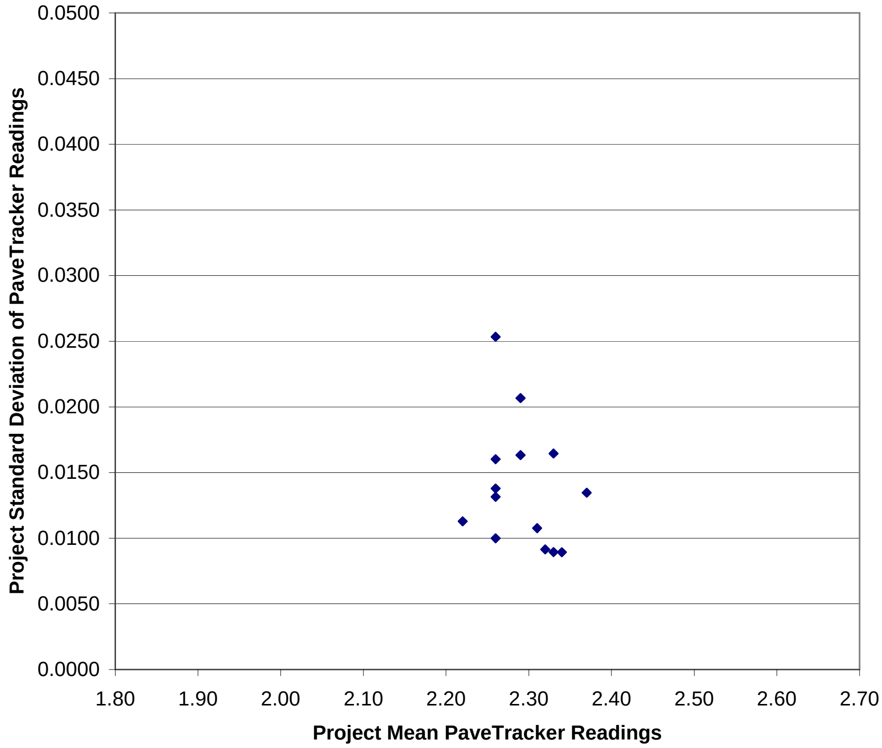

Figure A.16. PaveTracker adjusted mean readings versus standard deviation of PaveTracker readings

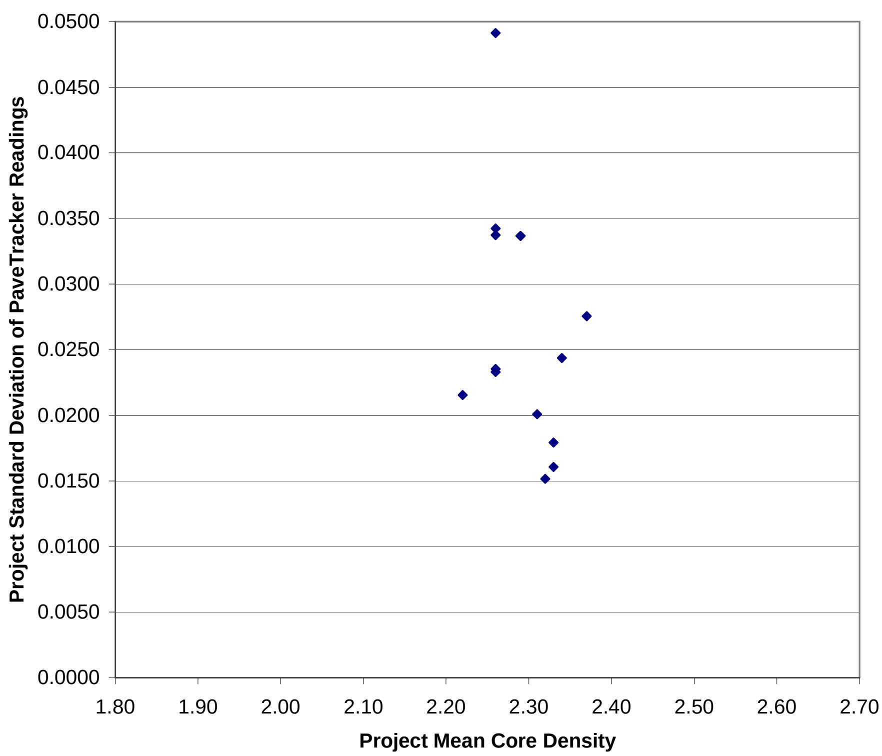

Figure A.17. PQI adjusted mean readings versus standard deviation of PQI readings